VOLUME LXX NUMBER 5

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

Edited by

GEORGE E. HALE
Mount Wilson Observatory of the Carnegie Institution of Washington

EDWIN B. FROST
Yerkes Observatory of the University of Chicago

HENRY G. GALE
Ryerson Physical Laboratory of the University of Chicago

DECEMBER 1929

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILLINOIS. U.S.A.

December 1929 Vol. LXX, No. 5

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY
AND ASTRONOMICAL PHYSICS

The Astrophysical Journal is published by the University of Chicago at the University of Chicago Press, 5750 Ellis Avenue, Chicago, Illinois, during each month except February and August. ¶ The subscription price is $6.00 a year; the price of single copies is 75 cents. Orders for service of less than a half-year will be charged at the single-copy rate. ¶ Postage is prepaid by the publishers on all orders from the United States, Mexico, Cuba, Porto Rico, Panama Canal Zone, Republic of Panama, Dominican Republic, Canary Islands, El Salvador, Argentina, Bolivia, Brazil, Colombia, Chile, Costa Rica, Ecuador, Guatemala, Honduras, Nicaragua, Peru, Hayti, Uruguay, Paraguay, Hawaiian Islands, Philippine Islands, Guam, Samoan Islands, Balearic Islands, Spain, and Venezuela. ¶ Postage is charged extra as follows: for Canada and Newfoundland, 30 cents on annual subscriptions (total $6.30); on single copies, 3 cents (total 78 cents); for all other countries in the Postal Union, 50 cents on annual subscriptions (total $6.50), on single copies 5 cents (total 80 cents). ¶ Patrons are requested to make all remittances payable to The University of Chicago Press, in postal or express money orders or bank drafts.

The following are authorized agents:

For the British Empire, except North America, India, and Australasia: The Cambridge University Press, Fetter Lane, London, E.C. 4. Yearly subscriptions, including postage, £1 *12s. 6d.* each; single copies, including postage, *4s.* each.

For Japan: The Maruzen Company, Ltd., Tokyo.

For China: The Commercial Press, Ltd., Paoshan Road, Shanghai. Yearly subscriptions, $6.00; single copies, 75 cents, or their equivalents in Chinese money. Postage extra, on yearly subscriptions 50 cents, on single copies 5 cents.

Claims for missing numbers should be made within the month following the regular month of publication. The publishers expect to supply missing numbers free only when losses have been sustained in transit, and when the reserve stock will permit.

Business Correspondence should be addressed to The University of Chicago Press, Chicago, Illinois.

Communications for the editors and manuscripts should be addressed to the Editors of The Astrophysical Journal, Yerkes Observatory, Williams Bay, Wisconsin.

The cable address is "Observatory, Williamsbay, Wisconsin."

The articles in this Journal are indexed in the *International Index to Periodicals*, New York, N.Y.

Entered as second-class matter, January 17, 1895, at the Post-office at Chicago, Ill., under the act of March 3, 1879. Acceptance for mailing at special rate of postage provided for in Section 1103, Act of October 3, 1917, authorized on July 15, 1918.

PRINTED IN THE U.S.A.

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME LXX DECEMBER 1929 NUMBER 5

THE SPECTROHELIOSCOPE AND ITS WORK[1]

PART I. HISTORY, INSTRUMENTS, ADJUSTMENTS, AND METHODS OF OBSERVATION

BY GEORGE E. HALE

ABSTRACT

The *spectrohelioscope* permits the *visual observation and analysis of the forms and motions of prominences at the sun's limb and of bright and dark flocculi on the disk.*

The *principle of the spectrohelioscope* was first suggested by Janssen in 1868, and successfully tried by Young in 1870 for observing the forms of prominences projecting beyond the limb, but was discarded by him when Zöllner and Huggins adopted a spectroscope with widened slit for this purpose. The spectrohelioscope was developed in 1924–1929 by Hale, who applied *high dispersion* to reveal *flocculi on the disk and a "line-shifter"* to vary the wave-length of the incident light during observation.

The inexpensive *instruments* described in this article, which comprise a horizontal *coelostat telescope* and *spectrohelioscope*, are suitable for a wide variety of observations. *Two oscillating slits* of easily variable amplitude or a *pair of square prisms* (Anderson's design) rotating before fixed slits may be used to give the *monochromatic* image of a portion of the sun, usually with the $H\alpha$ line.

The *adjustments* of the instruments are described in detail.

Methods of observing various types of prominences and flocculi and of analyzing their *forms* and *radial velocities* are then explained. Means of using the spectrohelioscope in conjunction with spectrographs or spectroheliographs are also described.

The possibility of obtaining the first rational explanation of many solar and geophysical phenomena by the aid of modern physics and chemistry, and the reciprocal advantages offered to these fundamental sciences through the study of matter acted upon by powerful forces in the atmosphere of the sun and sometimes apparently transmitted by solar eruptions to the higher atmosphere of the earth, place emphasis on the necessity of improving our methods

[1] *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 388.

of solar research. In previous papers I have described some of the unworked opportunities afforded by the spectrohelioscope, which is now easily within the reach of many amateur and professional observers. Even in the midst of a large city, under poor atmospheric conditions, it will yield valuable contributions in a field of astrophysics only partially explored and serve investigators in related sciences as a useful means of adding to their present laboratory facilities.[1]

As I have learned that several astronomers suppose the inexpensive instruments described in this paper to be intended chiefly for educational purposes, or merely to demonstrate the methods involved, I wish to correct this misapprehension. They are in fact instruments of research, capable of showing all of the phenomena described here as well as I can see them myself with my vertical spectrohelioscope, which in its present form is precisely equivalent, both mechanically and optically, to the spectrohelioscope illustrated in Plates IX, X, XI, and XII. The small coelostat also serves as well for these visual observations as the larger one needed for my work on solar magnetic fields and other investigations demanding very high dispersion.

ORIGIN AND DEVELOPMENT OF THE METHOD

Early history.—The well-known solar eclipse of August 18, 1868, following which Janssen in India and Lockyer in England succeeded for the first time in observing the spectra of prominences in full sunlight, needs no description in these pages. A few months later, while still in India, Janssen addressed to the Secretary of the Paris Academy of Sciences a letter which contains the essential principle of both the spectrohelioscope and the spectroheliograph. After referring to his observations with an ordinary spectroscope, he says that he was not satisfied with them and therefore devised a second method:

> Cette nouvelle méthode consiste, dans son principe, à isoler dans le champ spectral un des faisceaux lumineux émis par la protubérance, faisceau qui est

[1] I have had so many inquiries regarding the construction, adjustments, and use of the spectrohelioscope that I have found it necessary to bring together in this single paper a variety of descriptions and illustrations, a few of which have appeared elsewhere, but are included here for the sake of clearness.

déficient dans la lumière solaire, et à transformer ensuite les éléments linéaires des images protubérantielles dans les images elles-mêmes, par un mouvement rotatif assez rapide imprimé au spectroscope.[1]

The instrument subsequently built to accomplish this purpose has been described and illustrated by Millochau and Stefánik in this *Journal:*

It consists of a direct-vision spectroscope, in which the collimating lens is movable between two screws, permitting the spectrum to be displaced slightly. At the focus of the telescope lens is a second slit, the two jaws of which can be independently adjusted and used to isolate the desired radiation. This slit is observed with a positive eyepiece. The spectroscope thus described is contained within a tube, which can be moved rapidly about its axis by means of a system of gears. This instrument thus constitutes a spectrohelioscope, and was intended for the visual study of the prominences; but by substituting a sensitive plate for the eyepiece it might be immediately transformed into a spectroheliograph. M. Janssen's apparatus embodies the principal characteristics of the spectroheliograph, although his idea did not receive practical application during a score of years.[2]

In a paper read before the Royal Saxon Academy of Sciences on February 6, 1869, Zöllner criticized Janssen's method and suggested a widened slit as preferable. After pointing out that an oscillating slit would be simpler and better than a rotating spectroscope, he discussed the principles involved in the use of an oscillating slit and a widened fixed slit, and concluded in favor of the latter (for the observation of prominences projecting against the sky):

Nimmt man der Einfachheit halber an, die ganze Fläche, über welche sich der Spalt bei seiner Rotation oder Oscillation bewegte, wäre von der Protuberanz erfüllt, und setzt voraus, die Intensität des entstehenden Nachbildes wäre umgekehrt proportional jener Fläche (entsprechend einer gleichmässigen Ausbreitung des durch den ruhenden Spalt gehenden Lichtes über jene Fläche) so würde, unter Annahme der obigen drei Sätze, das Intensitätsverhältniss zwischen Grund und Protuberanz dasselbe bleiben, mag man

Erstens, durch Oscillation des Spaltes die Helligkeit des Protuberanzgebildes herabsetzen und hierdurch die Helligkeit des superponirten Spectrums oder Grundes (nach 2) unverändert lassen oder mag man

Zweitens, den ruhenden Spalt so weit öffnen, dass sich seine Oeffnung gerade über den Raum ausdehnt, über welchen sich im ersten Falle die Oscillation erstreckte. Hierdurch bleibt (nach 1) die scheinbare Helligkeit der Protuberanz

[1] *Comptes rendus*, **68**, 94, 1869. See also p. 713 in the same volume.

[2] *Astrophysical Journal*, **24**, 42, 1906.

unverändert, die des Grundes wird aber in demselben Verhältniss gesteigert wie sie vorher bei constantem Grunde abgeschwächt würde.

Man würde daher unter den gemachten Voraussetzungen das beabsichtigte Ziel viel einfacher auf dem zweiten Wege erreichen, wenn man stets dafür Sorge trüge, dass, der Blendung wegen, das intensive Licht des eigentlichen Sonnenkörpers nicht in den Spalt dringt.

Der Spalt brauchte dann nur gerade so weit geöffnet zu werden, dass die Protuberanz oder ein Theil derselben in der Oeffnung erschiene.[1]

It will be observed that this reasoning is correct only when the oscillating narrow second slit, proposed by Janssen to isolate the line, is omitted. When used, it reduces the brightness of the continuous spectrum without affecting the brightness of the prominence, thus invalidating the first assumption of Zöllner.

On February 13, 1869, Huggins applied the wide-slit principle to the observation of the forms of prominences at the sun's limb.[2] Zöllner himself first utilized this method on July 1 of the same year,[3] and it was also adopted by Lockyer, Janssen, Secchi, Respighi, Young, and other solar observers.

In his *Contributions to Solar Physics* Lockyer remarked:

At the very outset Janssen and myself attempted to accomplish this [i.e., to see the form of the prominences], Janssen by giving a rotary motion to a direct vision spectroscope, I by giving an oscillating motion to the slit, in which I was followed by Young, who afterwards expanded it.

He then went on to quote from Young (whose spectroscope with two oscillating slits is illustrated on p. 167 of Lockyer's book) and from Zöllner, to whom he gave the credit for devising the wide-slit method.

Young, who was the first American astronomer to apply the spectroscope to the observation of prominences, described in 1870 the first spectrohelioscope really capable of showing their forms projecting beyond the sun's limb (Janssen's apparatus was mechanically unsuitable for this, because of the rapid rotation required). After describing his new solar spectroscope, he continued as follows:

The eye-piece of the instrument has an apparatus attached, which, however, thanks to the high dispersive power, I find unnecessary.

[1] *Berichte der K. Sächsichen Gesellschaft der Wissenschaften zu Leipzig*, **21**, 78, 1869.

[2] *Proceedings of the Royal Society*, **17**, 302, 1869. His reference to the use of a second slit between the prisms and the observing telescope was subsequently corrected.

[3] *Op. cit.*, **21**, 145, 1869.

It was early proposed by Janssen to use a vibrating or rotating slit in order to make visible the form of a solar prominence, but as Zöllner has shown, the mere opening of the slit answers just as well, the light of the protuberance being diluted to precisely the same extent in either case.

It occurred to me in connection with a suggestion of Professor Morton, that by interposing at the focus of the eye-piece a diaphragm which should move with the vibrating slit, the light of the neighboring portions of the spectrum might be cut off and this dilution avoided. Mr. Clark has devised and constructed a very beautiful mechanical arrangement by which this simultaneous and accordant motion of slit and diaphragm is effected by the rotation of the small fly-wheel shown in Fig. 1.

But I find that although, seen in this way, the prominences appear very bright; yet the working of the apparatus always causes a slight oscillation of the equatorial, which interferes with the definition of details, and I prefer to work with the slit simply opened.[1]

In reviewing these articles, so long forgotten in the early literature of spectroscopy, one is struck by several points. Apparently, Zöllner's introduction of the convenient wide-slit method depended largely upon his failure to notice or appreciate the value of Janssen's proposed second slit for isolating the spectral line, which was also ignored by Lockyer. Young independently adopted a second slit, and was able to observe prominences with its aid. Nevertheless, he relinquished the possibilities afforded by his spectrohelioscope as soon as the fixed wide slit enabled him to see prominences outside the sun's limb. I can find no evidence that he ever looked for prominences on the disk with his oscillating slits, but in any event the linear dispersion of his spectroscope was insufficient to show any of them satisfactorily, unless of great intensity. The whole incident, like many others in the history of science, illustrates how a valuable principle may remain unused for decades, even when repeatedly published in widely read volumes.

It should be remembered, however, that it was not then a question of increasing the contrast, but of finding a means of seeing the forms and not merely the spectra of prominences projected against the comparatively faint dispersed light of the sky. The idea of setting the oscillating second slit on different parts of a line, and thus of employing the spectrohelioscope as a quick means of velocity analysis and for studies of the flocculi at different levels, apparently oc-

[1] *Journal of the Franklin Institute*, 60, 334, 1870.

curred to no one. As for prominences on the disk, although a few of exceptional intensity were seen there by Young and others with widened slit, the average prominence was evidently regarded as unattainable, so far as its form was concerned, when carried by the sun's rotation against the brilliant background of the photosphere. Secchi, however, gave voice in *Le Soleil* to a hope that must have been generally entertained:

> Ce qui serait à désirer maintenant pour faciliter encore davantage ces recherches, c'est la découverte d'un milieu parfaitement monochromatique pour les raies de l'hydrogène. On verrait alors l'image de ces flammes rouges comme on voit celles des taches. Ce milieu peut-il etre trouvé? Nous engageons les physiciens à diriger leurs recherches de ce coté.[1]

The spectrohelioscope accomplishes this purpose for limited areas and at the same time enables the wave-length of the transmitted light to be varied with the "line-shifter" or otherwise.

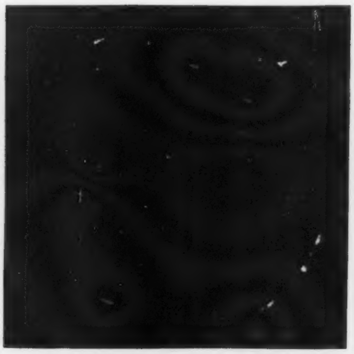
Recent progress.—Soon after we obtained on Mount Wilson the first spectroheliograms of the hydrogen flocculi with the $H\alpha$ line,[2] it occurred to me to try to observe their forms visually with the 30-foot spectroscope of the 60-foot tower telescope. This vertical spectroscope was of the Littrow type, with the slit in the optical axis of the tower telescope and an opening for a photographic plate at one side. Thus a second slit could be placed in the plate-opening in line with the first slit, an arrangement used when the instrument was employed as a spectroheliograph, either with a grating or with a large liquid prism mounted at the bottom of the 30-foot pit.

The distance between the slit centers is 6 inches, and it was a simple matter to mount in their place a circular brass disk, with its vertical bearing halfway between them. This disk was provided with a number of radial slits, which successively served in pairs as the first and second slits of a spectrohelioscope. As the first slit moved to the right, the corresponding $H\alpha$ line moved with the opposite slit at the same speed to the left, assuming the adjustments to be properly made and the field restricted so that only one pair of slits was illuminated at any time. Thus the observer, using a low-power posi-

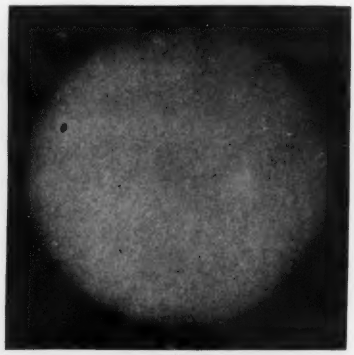
[1] *Op. cit.* (2d ed.; Paris, 1877), **2**, 16.

[2] Hale, *Contributions from the Mount Wilson Observatory*, No. 26; *Astrophysical Journal*, **28**, 100, 1908.

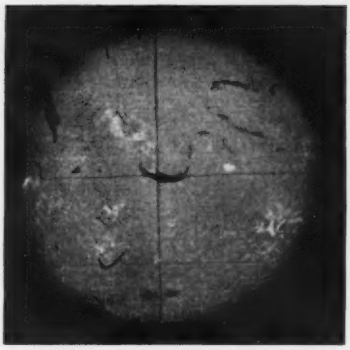
PLATE VII



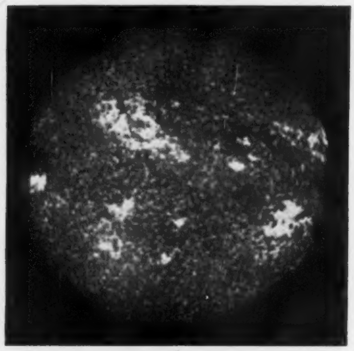
a



b

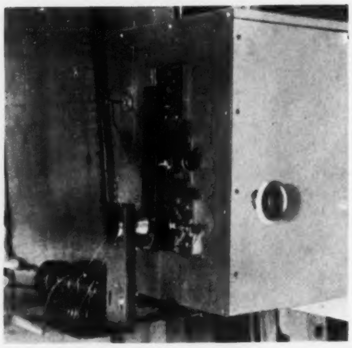


c



d

e



f

a. Prominences photographed with $H\alpha$ line, September 20, 1909
b. Direct photograph of the sun, July 31, 1927
c. Hydrogen flocculi, photographed with $H\alpha$ line, July 31, 1927
d. Calcium flocculi, photographed with K line, July 31, 1927
e. Coelostat temporarily used with 13-foot spectrohelioscope in 1924
f. Oscillating slits of 13-foot spectrohelioscope, 1924

tive eyepiece or a single lens focused on the second slits, should see a monochromatic image of a portion of the sun.

The method was feasible, but lack of time prevented me from determining the best spacing and width of slits, and thus from obtaining good results at that period. I kept the plan in mind, however, and after giving up the directorship of the Mount Wilson Observatory I decided to devote myself to its development. In the winter of 1923–1924 I accordingly set up in my garden in South Pasadena a coelostat telescope belonging to the Mount Wilson Observatory and a horizontal spectroheliloscope of 13 feet focal length (Plate VII *e, f*). This was of the type illustrated in the present article, but the (6-in.) grating and two concave mirrors were mounted in a long wooden box and the oscillating bar (used instead of a rotating disk) was provided at each end with a set of five slits, instead of the pair of single slits now employed. The wooden supports were unstable, and the mechanical parts rather crude. But by March, 1924, I had seen some dark hydrogen flocculi against the sun's disk and satisfied myself that when properly built the spectrohelioscope would prove a success.[1] Fortunately, I had chosen the diameter of solar image (2 in.), focal length of spectrohelioscope (13 ft.), and slit-width (0.003 in.) which I still find most suitable for use with the $H\alpha$ line in the brightest first-order spectrum of the gratings available (ruled with about 15,000 lines per inch).

When my solar laboratory, with a vertical coelostat telescope and the combined spectroscope, spectrohelioscope, and spectrograph shown in Plates XX–XXII, had been erected in Pasadena in 1925, it thus became merely a matter of transferring the same optical parts to their new and more substantial metallic mounting. Using at first the same oscillating bar with two sets of five slits (later reduced to a single pair of slits), I at once obtained excellent results. The prominences at the limb and the bright and dark flocculi all over the disk were easily seen, and by setting the second slit at different distances from the center of the $H\alpha$ line the variation of form and intensity with the wave-length and the radial velocities of the various parts of the prominences and flocculi could be quickly detected and com-

[1] *Mt. Wilson Communication*, No. 87; *National Academy of Sciences Proceedings*, 10, 361, 1924.

pared.[1] The value of the spectroheliocope for most of the purposes enumerated in the present paper then became apparent, and I decided to develop some of its possibilities, especially with the view of reducing its cost and thus rendering it more generally available.

Before describing the instruments since constructed for this purpose I must refer to a form of spectrohelioscope proposed by the late Mr. Thomas Thorp sometime before his death in 1914, a blue-print of which has kindly been sent me by Mr. Buss. This instrument, consisting essentially of a short-focus direct-vision spectroscope with a Thorp grating replica, mounted within a rotating drum carrying a large number of slits, is admirably designed and should serve on an equatorial telescope for the observation of prominences beyond the limb. Its dispersion would be too low, however, for satisfactory observations of the flocculi, though it might show those of greatest intensity, including the brightest eruptions on the disk.

Another project for a spectrohelioscope was described and illustrated in 1924 by Mr. F. Stanley, who first tried some experiments with a rotating disk with radial slits in 1912.

> The instrument consists of a rotating disc (2) in which are cut a number of radial slits. The light which forms an image of the sun or other object comes to a focus on the rotating disc at (16). The light passes through the slit and is collimated by the object glass (3), and passes through the deflecting system (4) and (4′) and the pentagonal prism (5). The dispersing element (17) is a high dispersion compound prism which forms an image by means of the object glass (7) on the disc at position (17). This slit image will be in monochromatic light and will pass out through the slit at (17) into the observing eyepiece (13).
>
> When the instrument is in use, the disc (2) is rotated, by means of a pulley (15) and an electric motor, at a speed which will eliminate flicker, and the object is then seen in monochromatic light corresponding to that for which the compound prism is set. When light of a different wave-length is required, a suitable deflecting prism is interposed at (18). The degree of purity will, of course, depend on the width of slits employed. The deflecting prisms (4) and (4′) are used to correct small errors of deviation due to the dispersing prism (17) and are driven by suitable gearing to make one complete revolution as the entrance slit passes the object.[2]

[1] Hale, *Publications of the Astronomical Society of the Pacific*, **38**, 97, 1926; *Mt. Wilson Communication*, No. 97; *National Academy of Sciences Proceedings*, **12**, 286, 1926; *Nature*, July 3, 1926, Supplement; *ibid.*, **118**, 420, 1926; *ibid.*, **119**, 708, 1927.

[2] *Nature*, **114**, 683, 1924.

I prefer the simpler form of spectrohelioscope described in the present article, in which no revolving deflecting prisms are needed.

In a letter dated January 6, 1927, Mr. Evershed wrote me as follows:

> You may be interested to hear that I have recently made a spectrohelioscope attachment to my spectroheliograph, and have seen for the first time the dark prominences on the sun's disc. It is not so simple to construct as in your design, because the light coming from the prisms is reflected out at right angles near to the first slit, as in the sketch that I enclose, so that I have to construct a horizontal rocker with arms about a foot long and at right angles. This is pivoted over the mirror M2, and the end of each arm carries a vertical slit made of aluminium sheet. The whole is made as light as possible, and braced together to give rigidity, yet at any slight jarring in the running of the electric motor, such as happens when the joint in the belt runs over the small motor pulley, there is a tendency for the $H\alpha$ line to move slightly on the slit, and then one sees dark shadings moving over the portion of the sun's disc under observation. I hope to cure this defect eventually.

Evershed's spectroheliograph, it should be added, is of the Littrow type, of 16 feet focal length, provided with a 6-inch meniscus collimator lens and two very fine 45° prisms of the same aperture, used with a plane mirror behind them.

INEXPENSIVE INSTRUMENTS

A brilliant solar eruption, beautifully seen in all its changing forms on the sun's disk only a few days after my improved spectrohelioscope had been brought into use, and followed by a violent terrestrial magnetic storm,[1] emphasized for me the importance of establishing a chain of such instruments around the world. With their aid the sun could be kept under observation almost continuously, thus rendering practically certain the detection of all similar outbursts and greatly facilitating the study of their relationship to terrestrial phenomena. At present many of them are missed and progress is correspondingly slow.

The practicability of building small but efficient solar telescopes and spectrohelioscopes was soon proved by experiments with my larger instruments, and several designs were prepared, some of which

[1] Hale, *Mt. Wilson Communication*, No. 97; *National Academy of Sciences Proceedings*, **12**, 286, 1926.

have been briefly described.[1] The instruments illustrated in the present article embody later improvements and have been so satisfactory in performance that a more detailed description, including further information regarding their design, adjustment, and use, is due.[2]

The necessary equipment, which in reality constitutes a small but efficient solar observatory, includes: (1) a telescope, which in its simplest and least expensive form comprises a coelostat, second mirror, and single lens; (2) a spectroscope, of about 13 feet focal length, of the reflecting or Littrow type; (3) a pair of oscillating slits or some other device for producing the necessary rapid relative motion of the slits and solar image.

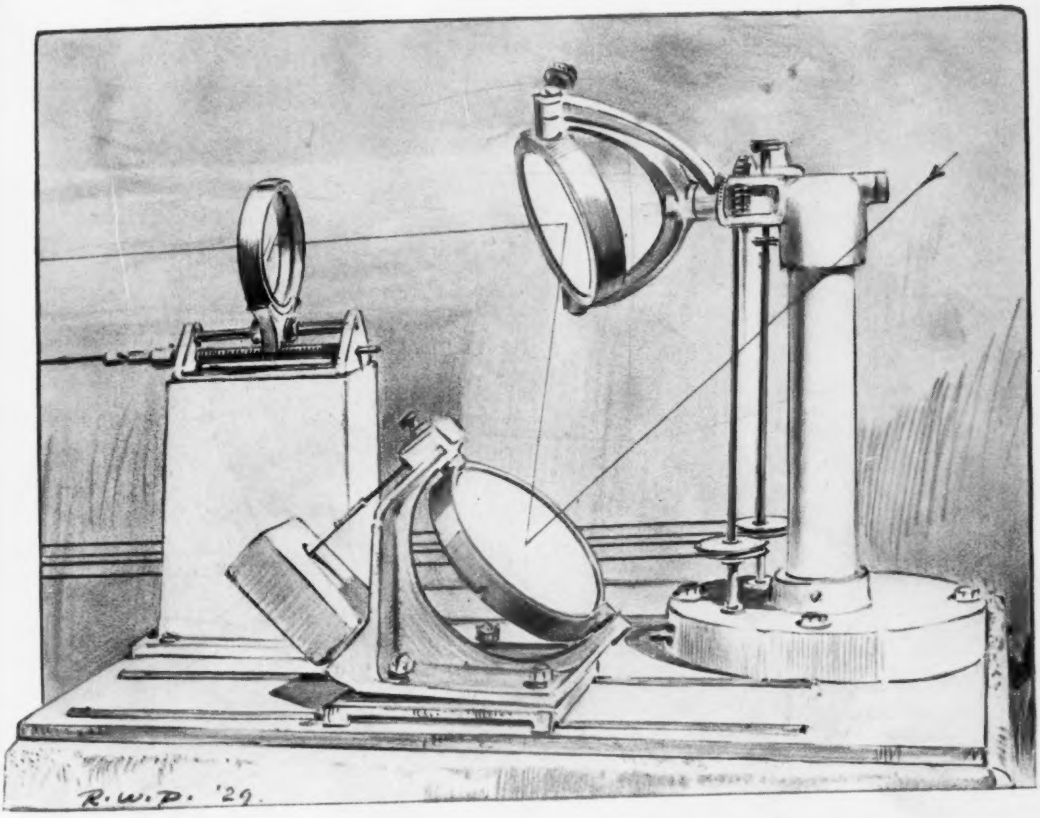
The general arrangement of the telescope and spectrohelioscope is shown in Figure 1, from a sketch by Mr. Russell W. Porter. Figure 2, from a drawing by Mr. Nichols, of the Mount Wilson Observatory, gives the dimensions and relative positions of the piers. If made of concrete, "floated" on a bed of sand 6 inches thick, and not in direct contact with the floor, they will be stable and will not easily transmit vibrations. I may add, however, that I have also found heavy wooden boxes, filled with earth, to serve very satisfactorily as piers.

The telescope.—Mr. Porter's drawing of the coelostat, second mirror and lens (Plate VIII) is so clear in itself that little explanation is required. The mirror of the coelostat ($5\frac{1}{2}$ in. in diameter) and the second mirror ($4\frac{1}{2}$ in.) are made of ordinary plate glass, $\frac{1}{2}$ inch thick, with silvered front surfaces, plane to about a quarter of a wave. Glass is perfectly satisfactory in such a case; it would be a waste of expense to use fused silica for such small mirrors. The coelostat is driven by an ordinary (two-dollar) clock movement with escapement, as the intermittent motion is not perceptible under the low powers employed. The two slow motions for rotating or inclining the second mirror, thus bringing any part of the solar image upon the first slit of the spectrohelioscope, are shown here controlled by cords within reach of the observer, but these may be replaced by light rods

[1] Hale, *Nature*, **121**, 676, 1928; *Scientific American*, **140**, 302, 1929; *ibid.*, p. 436, 1929. See also *Amateur Telescope Making* (2d ed.), Part IX (Scientific American Publishing Co., 1928).

[2] Such instruments can be purchased from Howell & Sherburne, 88 N. Delacy Ave., Pasadena.

PLATE VIII



Coelostat, Second Mirror, and Telescope Lens

or tubes. The 4-inch single lens of 18 feet focal length can also be focused by the observer. A single lens serves perfectly for observa-

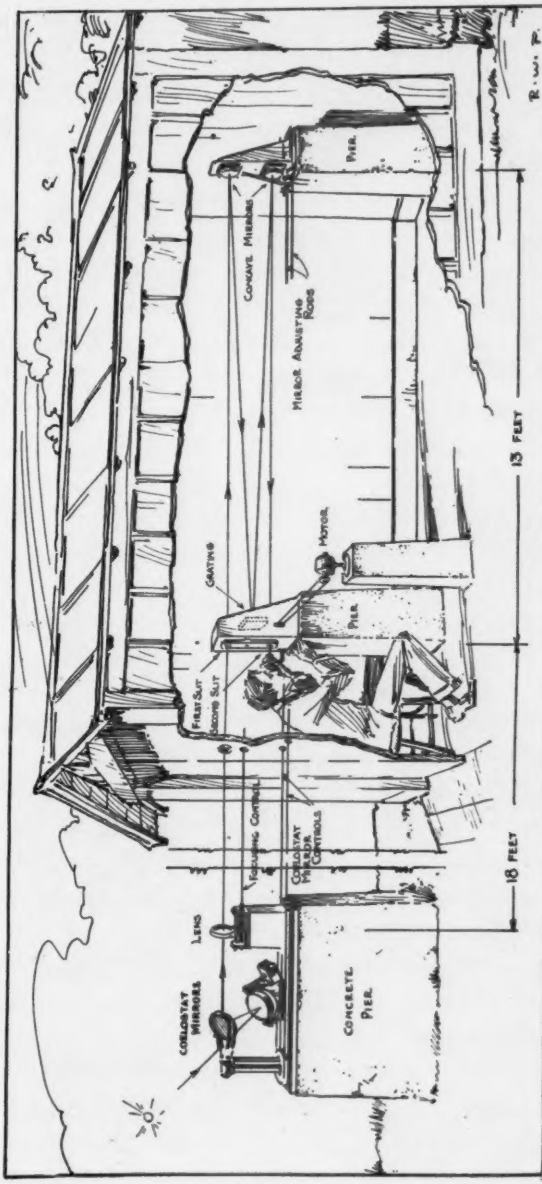


FIG. 1.—General arrangement of coelostat telescope and spectroheliscope

tions with monochromatic light, but it is poorly adapted for drawings of the directly enlarged solar image, often needed to record the forms and positions of spots and faculae. Perhaps the simplest way to obtain such an enlarged image is to mount a 1- or 2-inch telescope with eyepiece within the building, at one side of the spectrohelioscope and making an angle of about 20° with it. By turning the second mirror so as to send a beam of parallel rays past one side of the 4-inch lens, instead of through it, this small telescope can be fed with sunlight

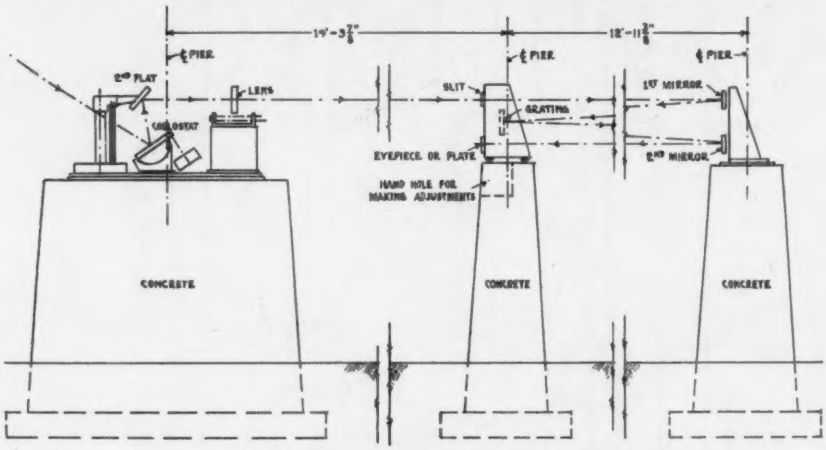


FIG. 2.—Concrete piers for coelostat telescope and spectrohelioscope

and the enlarged solar image sketched upon paper fastened to a drawing screen fixed at the focus of the eyepiece.

If desired, the coelostat, second mirror, and lens can be erected at the summit of a light steel tower and the beam sent vertically downward to the spectrohelioscope, mounted in a well in the earth beneath it. Such a tower telescope, with a small observing house at its base, takes little space and can be very cheaply built from standard materials. Or the coelostat, etc., can be placed on top of a building (if free from vibration) and the beam directed through a hole in the roof or down an open shaft.

I have not built a spectrohelioscope for attachment to an equatorial telescope, but this should not be difficult, especially if Anderson's rotating prisms (Plate XIV) are used instead of oscillating slits (to avoid vibration). A two-mirror or Littrow spectroscope of about

13 feet focal length, clamped to the telescope tube and receiving its light from the solar image by the aid of two right-angle prisms, would be needed in this case. The coelostat telescope and fixed spectroheliosope are more convenient, however, and much less expensive.

The spectroscope.—If the angular dispersion used is assumed to be that of the first-order spectrum of an original plane grating ruled with about 15,000 lines per inch, a focal length of 13 feet will be found suitable for the spectroscope. This gives an $H\alpha$ line of sufficient width (about 0.008 in.) for use with first and second slits 0.003 or 0.004 inch wide. If narrower slits are employed, the dust lines are likely to be troublesome, even if the brightness of the spectrum is great enough. After trying focal lengths as short as 42¼ inches and as long as 75 feet, I can recommend 13 feet to anyone possessing such a grating as I have described, very bright in the first order.

As for the design of the spectroscope, I prefer that shown in Plates IX, X, XI, and XII. In this arrangement the rays diverging from the first slit fall on a spherical concave mirror 3 inches in diameter, which renders them parallel and returns them to the grating. This is rigidly mounted near the first slit, just below the diverging beam. The grating is set at such an angle as to return the spectrum to a second concave mirror exactly like the first and mounted below it. This is illuminated only by the region centering on the line employed (usually $H\alpha$), and as the upper (collimating) mirror is concealed from the observer by a suitable diaphragm, the intensity of the diffuse light entering the eye is greatly reduced, thus adding to the visibility of faint prominences or flocculi.

The lower concave mirror forms an image of the spectrum on the second slit, with which $H\alpha$ is brought into coincidence. The second slit is observed through a positive eyepiece (a single lens will usually suffice) having a magnifying power of from two to four diameters. Sunlight is excluded from the room by a tube, extending from the first slit to the opening in the wall. The darker the room the better one can see the structure of the solar atmosphere.

An alternative design for a spectrohelioscope, with slits horizontal instead of vertical, is shown in two previous articles.[1] This permits the use of slits with centers only 3½ inches apart, and consequently of a

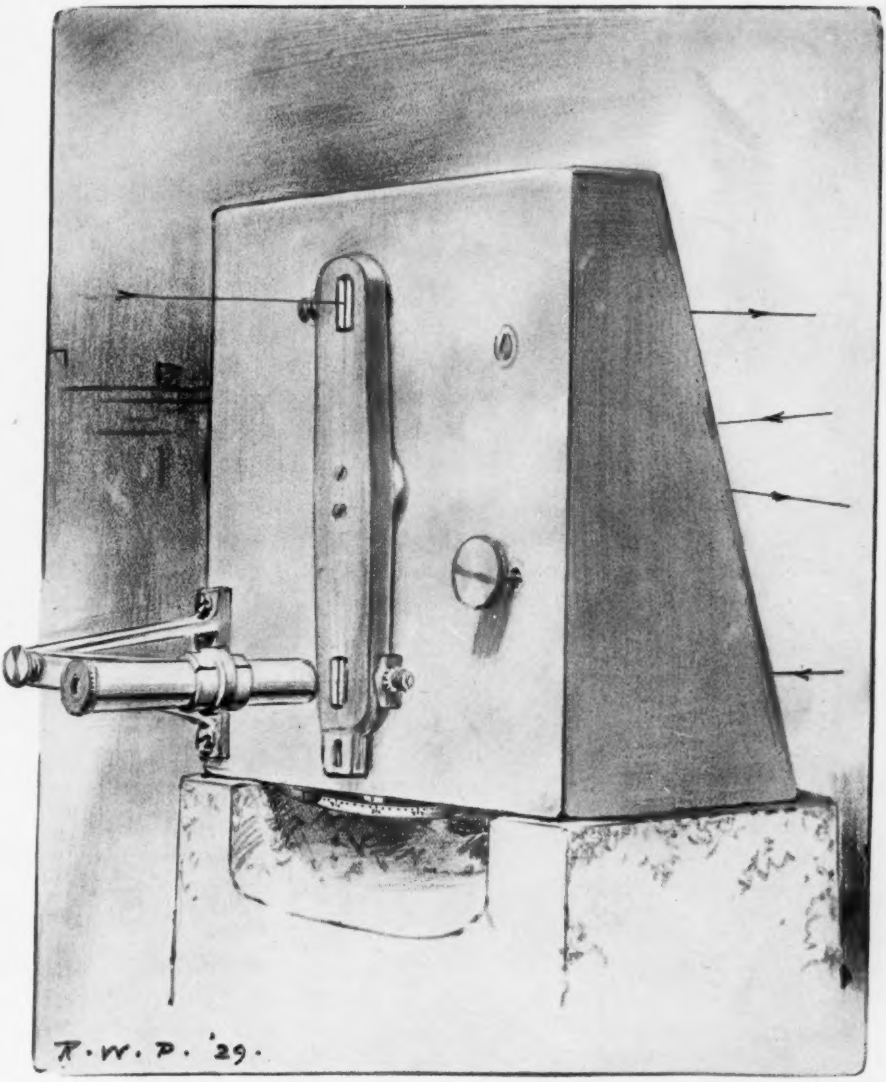
[1] Hale, *Nature*, **121**, 676, 1928; *Scientific American*, **140**, 302, 436, 1929.

very light oscillating slit system. The chief idea of this spectrohelioscope was to simplify construction and reduce cost. I prefer the vertical slit arrangement, but the horizontal slit design is mentioned here because of its bearing on the possible substitution of a standard Littrow spectroscope for the two-mirror reflecting spectroscope adopted for both of the preceding instruments.

Perhaps the simplest of all spectroscopes for the purpose in view is one of the Littrow type, in which a single crossed lens, with grating mounted behind it, is used instead of the two concave mirrors and grating mount already shown. The radius of curvature of the front surface of this lens should be equal to its focal length (13 ft.), thus returning the sunlight reflected from this surface to a focus on the first slit and keeping it out of the observer's eye. The light reflected from the more highly curved second surface produces another image of the first slit at a point on the same axis not far from the lens, where a small flat bar should be mounted to conceal it. The intensity of the white light scattered by the illuminated face of the grating naturally depends upon the grating employed and also upon the width of the first slit and the focal length of the spectroscope. I have seen the flocculi and the prominences beyond the limb fairly well with such a Littrow arrangement, but the contrast was less pronounced than with the double-concave-mirror form, which I therefore prefer.

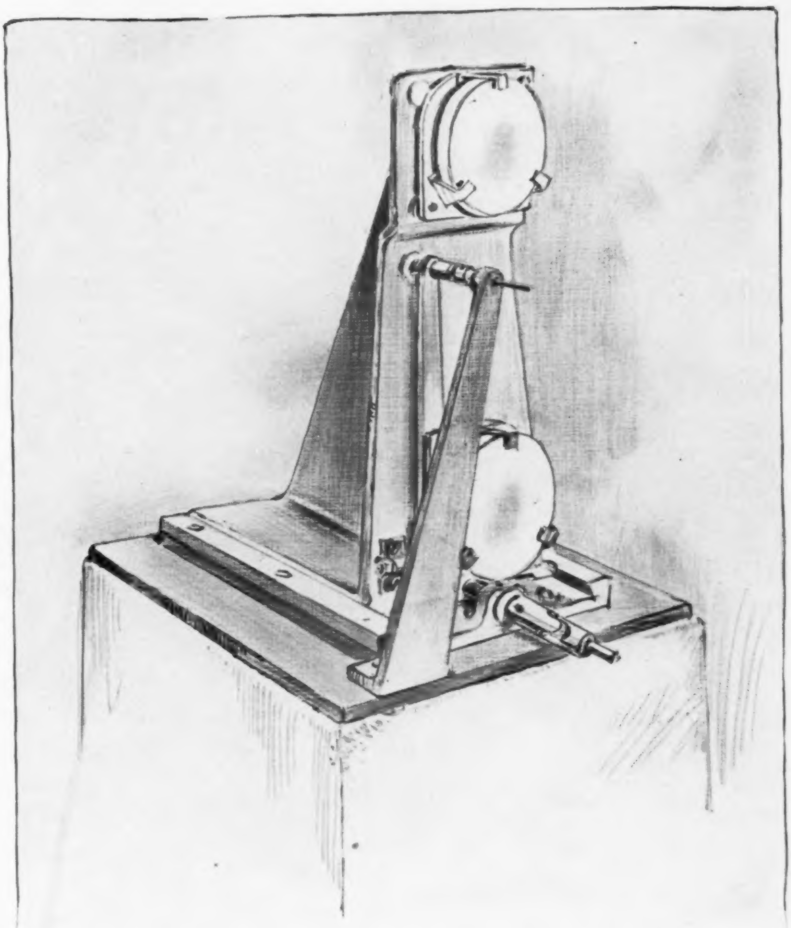
Two prisms, with a plane mirror returning the dispersed beam through them, can be used in place of a grating. This equivalent of four prisms gives less dispersion in the $H\alpha$ region than the first order of a grating, unless glass of considerably higher refractive index than that at my disposal is available. I strongly recommend a grating, but it must be an original ruling, preferably of the 4-inch size (ruled area approximately $2\frac{1}{2}\times 3$ inches). Such gratings are obtainable from J. W. Fecker, 1954 Perrysville Avenue, Pittsburgh, Pennsylvania, and from Adam Hilger, Ltd., 75*a* Camden Road, London, N.W. 1, England. Thus far I have been unable to obtain a reflecting-grating replica good enough to meet the needs of the spectrohelioscope. I have also tested many transmission replicas without finding one of suitable quality. Nevertheless, I still hope that some improved method of copying gratings may ultimately be perfected.

PLATE IX



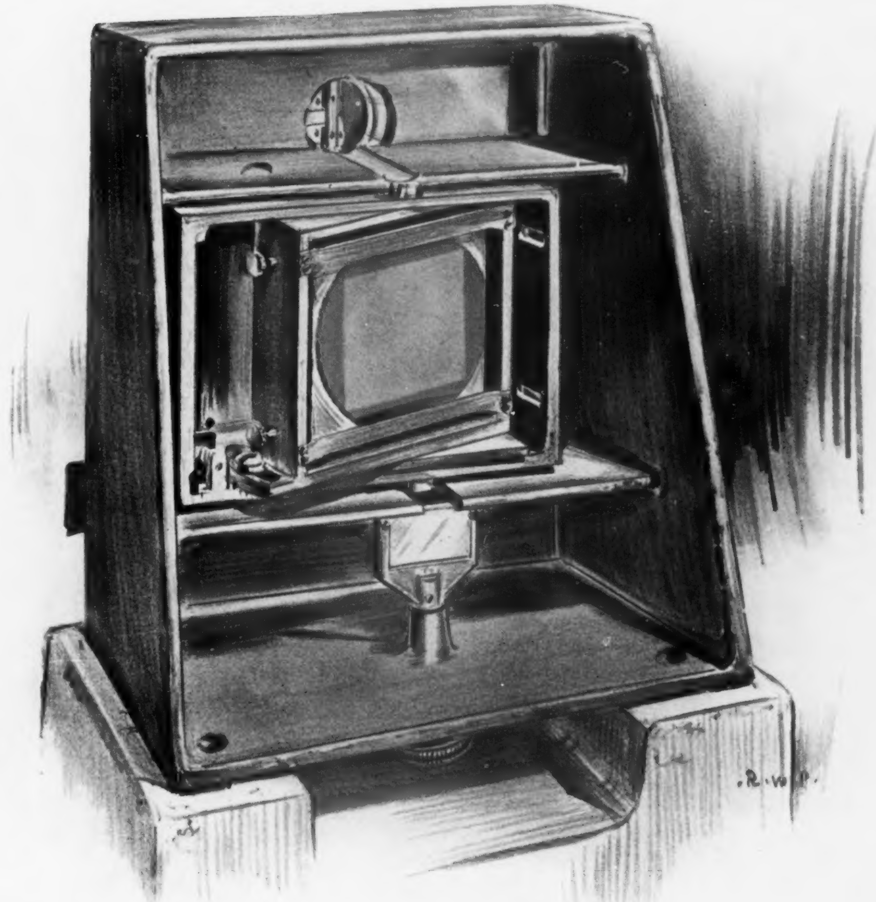
Oscillating Slits and Eyepiece of Spectrohelioscope

PLATE X



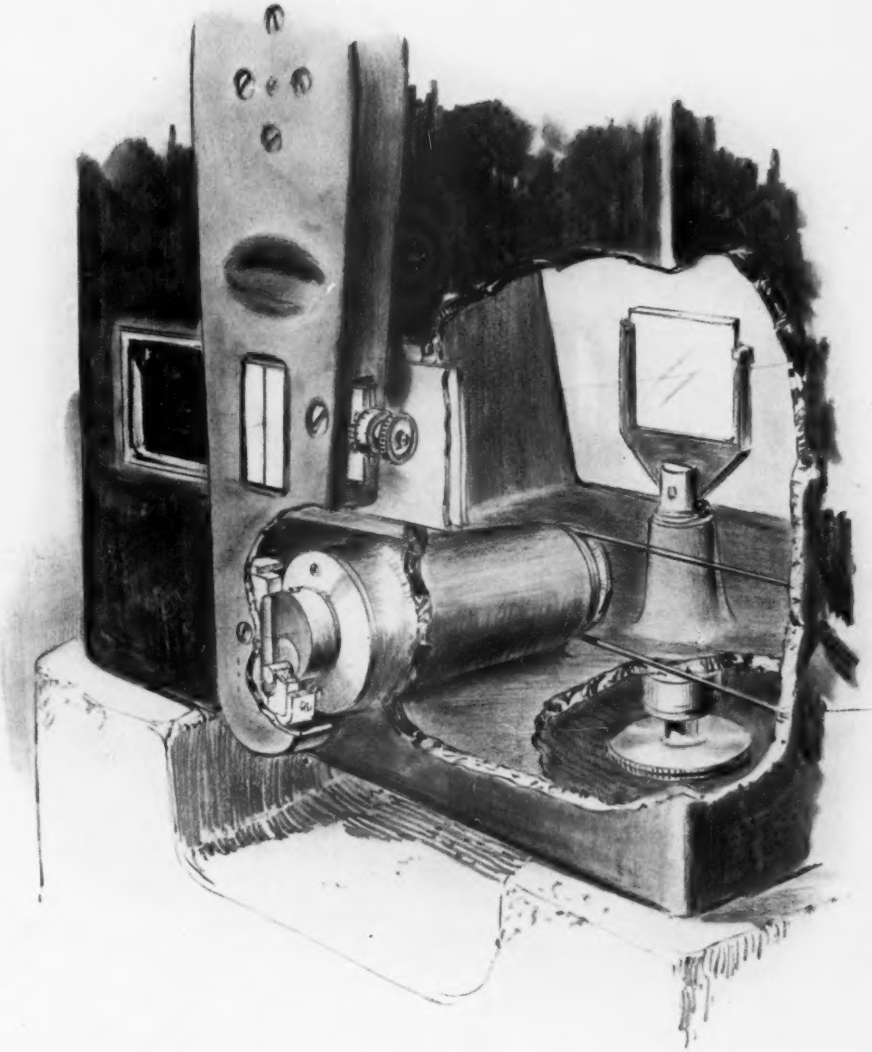
Concave Mirrors of Spectrohelioscope

PLATE XI



Grating Support and Line-Shifter

PLATE XII



SECOND SLIT, DRIVING MECHANISM, AND LINE-SHIFTER

Production of the monochromatic solar image.—The original Janssen-Lockyer method of observing the spectra of prominences, supplemented by the use of a wide slit to reveal their forms, serves admirably when it is only a question of reducing the brightness of the sky by the dispersion of the spectroscope. If, however, the sky were as bright as the sun's disk, the prominences, except in rare cases, would be rendered invisible by its overpowering brilliancy.

Professor Charles A. Young, one of the ablest and most experienced of solar observers, stated the case as follows in his well-known book, *The Sun:*

> In a few instances the gaseous eruptions in the neighborhood of a spot are so powerful and brilliant that with the spectroscope their forms can be made out on the background of the solar surface in the same way that the prominences seen at the edge of the sun. In fact, there is probably no difference at all in the phenomena, except that only prominences of most unusual brightness can thus be detected on the solar surface.

Secchi's reference to the need of a method of observing prominences against the disk has already been quoted. Here, as the spectroheliograph first showed in 1903,[1] they usually appear as dark flocculi, because their comparatively cool gas absorbs the light of the hotter photosphere. Bright flocculi also occur, due to brighter hydrogen, usually found at lower levels. When these flocculi are intensely bright their forms can be made out roughly against the disk with a spectroscope by widening the slit, as already noted. Extremely dark flocculi may also be seen imperfectly in the same way, as Mr. Buss has shown; but these are exceptional cases. Most of the flocculi, bright or dark, disappear when the slit is widened sufficiently to include their forms. The weakening and disappearance of most of the lines of the solar spectrum, observed when the purity is decreased by widening the slit of a spectroscope, illustrate this effect. The spectrohelioscope retains the strong contrast given by a narrow slit, and thus renders visible the flocculi, both faint and intense, against the brilliant disk.[2] It also shows the prominences at the limb against a

[1] Hale and Ellerman, *Publications of the Yerkes Observatory*, **3**, Part I, 1903; *Astrophysical Journal*, **19**, 41, 1904.

[2] The "motion forms" of Lockyer (*Contributions to Solar Physics*, Fig. 149), due to distortion of the hydrogen lines, are not to be confused with the true forms of the flocculi (see below, p. 295).

nearly black background. Moreover, as a narrow slit prevents the overlapping of images observed in white light with a wide slit, the spectrohelioscope renders visible the structure of sun-spots, which can be sharply seen with light from any part of the solar spectrum away from the dark line.

As we have seen, the spectrohelioscope may thus consist of a spectroscope of considerable dispersion, provided with a pair of oscillating slits and a "line-shifter" for varying the wave-length of the light transmitted by the second slit. As in the case of the spectroheliograph, however, a monochromatic image can be produced either by motion of narrow slits with respect to the solar image, or by motion of the solar image with respect to the slits. The chief difference between the two instruments lies in the fact that the spectroheliograph builds up its image gradually, slit-width by slit-width, by a slow motion of the slits or of the solar image with respect to the photographic plate, while the spectrohelioscope must reveal a considerable area of the sun at once to the eye, which obviously could not see the forms of the flocculi through slowly moving slits a few thousandths of an inch wide. Hence the rapid motion of the slits or of the solar image required for the spectrohelioscope.

I have tried successfully three systems of moving slits, as follows: (1) an oscillating bar carrying single slits at each end; (2) an oscillating bar carrying three or more slits at each end; (3) a rotating disk carrying many radial slits.

Three means of producing rapid motion of the solar image with respect to fixed slits have also been devised:

1. An oscillating plane mirror, so mounted in conjunction with a second plane mirror that the second slit can be viewed in another part of the same mirror system. This was suggested by Dr. Sinclair Smith.
2. A square prism of glass, mounted before each of the slits, rotating uniformly about an axis parallel to them. The portion of the solar image under observation reaches the first slit through one prism, while the resulting fixed monochromatic image is seen in an eyepiece focused through the other prism on the second slit. This device is due to Dr. J. A. Anderson.
3. An oscillating right-angle prism, mounted with its edge parallel to the slits and its hypotenuse surface normal to their plane. In this arrangement, previously used in somewhat different form on the spectroheliographs of our

60-foot and 150-foot tower telescopes at Mount Wilson, and now on that of my Solar Laboratory in Pasadena, the solar image moves at twice the speed of the prism.

All three of these devices for use with fixed slits are here supposed to be employed with a spectroscope in which the apparent motion of the solar image, as observed through the second slit, is opposite in direction to the actual motion of the solar image across the first slit. In this case, when looking at the second slit through an extension of the oscillating or rotating optical system that causes the motion of the solar image, the effect of this motion is exactly compensated and the monochromatic image appears at rest. The same devices can be adapted for use with spectroscopes of other types.

A more detailed consideration of several of these schemes may now be given.

Oscillating slits.—The simplest arrangement for the vertical-slit spectrohelioscope is a single pair of oscillating slits, as shown in Plate IX. The bar supporting the slits is of sheet aluminum $\frac{1}{16}$-inch thick, hammered into shape over a suitable form. This bar is mounted on a conical bearing, resembling that of a jeweler's lathe, which permits all wear to be taken up for the purpose of eliminating vibration. The two slits are of simple design, one jaw being movable by a micrometer screw with divided head. The upper (first) slit is fixed on the bar, while the second slit can be rotated so as to make it exactly parallel to the $H\alpha$ line. This slit is also provided with small windows at top and bottom, permitting the upper and lower end of the line to be seen when the oscillating bar is at rest. In this way three adjustments can be effected: parallelism of the slit to the line, coincidence of slit and center of line when the circle of the line-shifter (see below) reads zero, and precisely equal motion of slit and line when the oscillating bar is moved (see "Adjustments").

The driving mechanism is shown in Plate XII and Figure 3. A steel pin projecting from the face of a small brass disk driven by an electric motor of adjustable speed is so mounted that it can be moved toward or away from the center of the disk, thus permitting the amplitude of oscillation to be varied. This pin travels in a slot of adjustable width at the end of the oscillating bar. When properly

made and adjusted the bar can be very rapidly oscillated without setting up troublesome vibration. The amplitude employed in my instruments is usually about $\frac{1}{4}$ inch, and the speed of the motor is regulated until the point of least flicker and vibration is found.

This driving device naturally involves a maximum slit velocity at the middle of an oscillation, slowing down to zero at each reversal of direction. Consequently the rectangular monochromatic image of a portion of the sun seen through the eyepiece focused on the second slit is brighter near the edges than at the center. In practice this is not objectionable. It can be reduced or completely eliminated, if desired, by multiple slits or revolving disks.

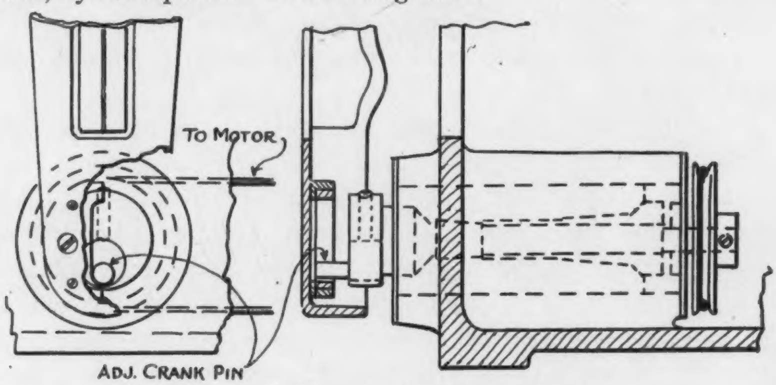
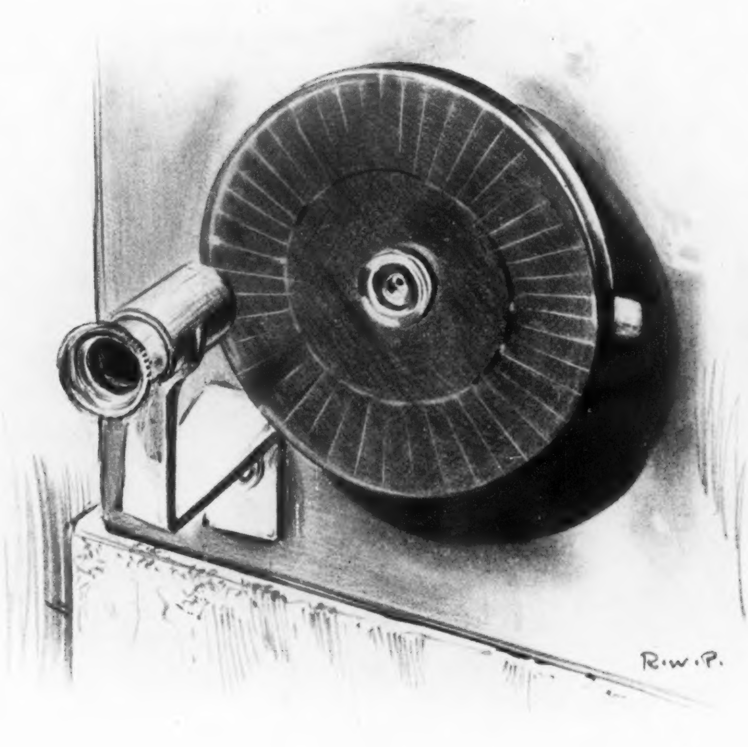


Fig. 3.—Driving mechanism for oscillating slits

The use at each end of the oscillating bar of three or more slits permits the rate of oscillation to be reduced (for the same degree of flicker) but calls for a fixed distance between consecutive slits, corresponding to invariable amplitude in the case of a pair of single slits. This distance must be slightly less than the width of a fixed window, or wide slit, mounted on the collimator axis just below the central position of the middle (oscillating) slit, so as to permit only one of the "first" slits to illuminate the collimator mirror at any moment. The amplitude of the oscillating bar must of course be increased sufficiently to bring all the slits successively into play. As for the slits themselves, they may be of fixed width (as in my first spectrohelioscope) or adjustable.[1] If a fixed window, such as that behind the first slits, is mounted centrally behind the second slits, a

[1] We have designed closely spaced adjustable slits of a very simple type.

PLATE XIII



SPINNING DISK WITH RADIAL SLITS

single monochromatic image will be seen. If not, this image will be flanked on both sides by other images. If it be assumed that the central second slit falls on $H\alpha$, these supplementary images will be given by light from the continuous spectrum outside of $H\alpha$. Thus, if desired, the $H\alpha$ flocculi above a group of sun-spots may be seen simultaneously in the same field of view with the spots themselves. This is often convenient, especially if a window is used behind the second slits of such width and adjustment as to show an $H\alpha$ image beside only a single continuous-spectrum image of the spots. Obviously this could be obtained with a combination of a single first slit and a double second slit. However, the line-shifter permits such a quick transition from $H\alpha$ to a continuous-spectrum image that recently I have not often employed multiple slits.

In a spectroscope of great focal length, such as the 30-foot spectrograph of the 60-foot Mount Wilson tower telescope, the diffuse light from the grating and the inclination of the spectral lines with a Littrow spectrograph are so slight that one is tempted to use a rotating disk carrying many radial slits—an arrangement that appealed to me at the outset because of its simplicity and the complete absence of flicker. Recently I have obtained fairly good results in this way, even with a focal length of 13 feet. One of the disks, in which fifty radial slits were cut by Mr. Hitchcock on the face of a glass disk coated with silver or a uniform film of Duco paint, is shown in Plate XIII.[1] This method, however, has several disadvantages compared with the oscillating bar and pair of single slits, among which the invariable slit-width and spacing and considerable inclination of the lines in certain spectroscopes may be mentioned. If I could afford the time I should nevertheless be inclined to develop it further, perhaps introducing adjustable slits and other changes. (I have already devised a simple optical method of bringing inclined spectral lines into precise coincidence with radial slits.)

Much more might be said regarding moving slits of various forms, especially those adapted for use with other kinds of spectroscopes. I must pass on, however, to the type of spectrohelioscope in

[1] The slits were cut on a Brown and Sharpe milling machine with a special tool. As the best spiral head is hardly accurate enough for spacing the slits, a divided circle with microscopes was employed.

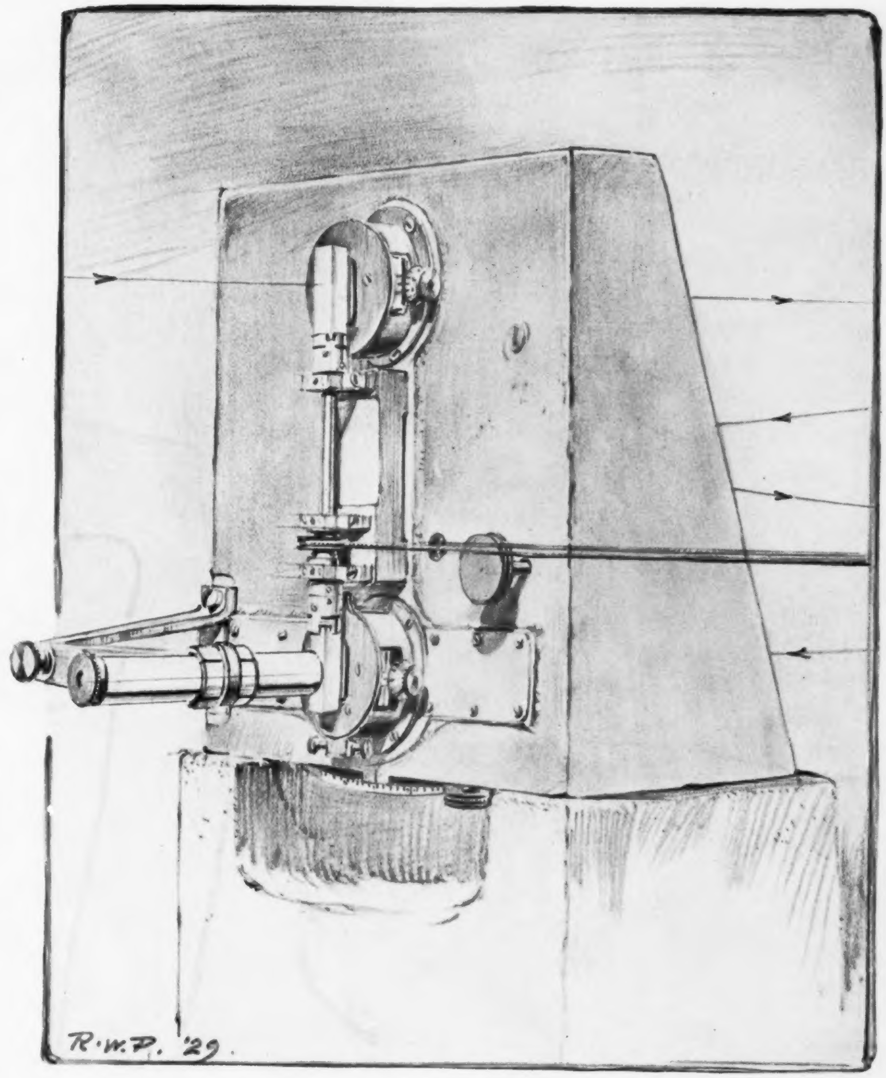
which two fixed slits are employed, with devices for producing the necessary relative motion of the sun's image. On page 280 I have mentioned three of these, all of which could doubtless be made to give excellent results. Only one has been adequately developed, the ingenious scheme suggested by Anderson to give a monochromatic image completely free from the effects of flicker and instrumental vibration.

Rotating prisms.—Plate XIV illustrates Anderson's device, in the form which I have adopted for the spectrohelioscopes built by the Mount Wilson Observatory and loaned to solar observatories widely distributed in longitude. Two rectangular prisms, square in cross-section, are mounted on a single shaft driven by a small electric motor. The upper prism receives the direct sunlight and transmits it to the first slit, on which the solar image is focused. Evidently the width of the area transmitted depends upon the width of the prism face and the index of refraction of the glass. As the prism rotates, this area is moved by the varying refraction across the slit and this process is repeated four times in each revolution. The second prism, rotating at the same speed, precisely compensates for the action of the first prism, and spreads before the eye a flicker-free monochromatic image of the area in question. When equipped with well-made prisms, accurately aligned, this admirable method gives beautiful results. The use of fixed slits simplifies the adjustment of the spectroscope, and the uniform rotation eliminates the dangers of vibration. It is true that with a single pair of prisms it is not possible to change the amplitude, which limits the brightness of the monochromatic image seen with a given slit-width. This can be done with oscillating slits, as already stated.[1] But for most purposes I can recommend Anderson's prisms, which are readily adaptable to existing Littrow spectroscopes.

Line-shifter.—Thus far we have considered the spectrohelioscope

[1] Since this article was put in type we have devised a simple attachment which will permit the amplitude of oscillating slits to be quickly varied while they are in motion. This will enable us to use a very small amplitude for the study of faint details on the dark center of $H\alpha$, and greatly to increase the amplitude (thus protecting the eye by holding down the brightness) when passing beyond the dark line on to the bright continuous spectrum. The same device, combined with a right-angle prism above the first slit for rotating the solar image, can also be used as a micrometer for measuring the dimensions of flocculi or their distance from sun-spots.

PLATE XIV



ANDERSON'S ROTATING PRISMS, FOR USE WITH FIXED SLITS

chiefly as a means of seeing directly such structure as is revealed photographically by a spectroheliograph with its second slit fixed at a given wave-length. The possibility of instantly varying the wave-length of the transmitted light while visual observations are in progress introduces a new and valuable element, applicable in the comparison of the forms of flocculi corresponding to different parts of the $H\alpha$ line, the study of the relationship of the flocculi to neighboring sun-spots, the instant measurement of radial velocities, and the rapid velocity analysis of prominences and flocculi.

Any simple method of varying the relative position of the second slit and line may be employed. In my first spectrohelioscope the bearing that carried the oscillating bar was mounted on a support movable by means of a micrometer screw. Another method would be to move the first or second slit separately, most easily done when the Anderson prisms are employed. On the whole, however, I recommend the use of a piece of approximately plane-parallel glass, mounted just behind the second slit on a steel shaft, which is rotated by means of a milled head. Concentric with the shaft and milled head is a circular arc of $3\frac{1}{4}$-inch radius, with edge divided into degrees, or provided with a wave-length scale (shown in Plates IX and XIV. The arc also carries near its circumference two adjustable brass stops, which can be clamped at any distance from the zero of the circle. The stops are sheathed with short pieces of rubber tubing, so as to prevent jar when the arc is moved rapidly back and forth between these limits. They permit the line-shifter to be employed like a "blink" comparator, facilitating the instant comparison of the forms or positions of prominences or flocculi corresponding to any part of the line with sun-spots or faculae seen by light from beyond its extreme boundaries. The adjustment and use of the line-shifter will be described more fully below.

INSTRUMENTAL ADJUSTMENTS[1]

Horizontal coelostat telescope.—1. Level the coelostat and adjust its polar axis to correspond with the latitude of the observing station.

[1] Most of these directions will be quite unnecessary to solar spectroscopists. They are given in detail because of the fact that several spectrohelioscopes are being erected or used by those who have had little or no experience in solar spectroscopic work. The directions refer to spectrohelioscopes with vertical slits.

2. Set the axis of the coelostat and the rails on which it slides in a north and south line.

3. See that the centers of the second mirror, the lens cell, the first slit of the spectrohelioscope, and the upper concave mirror lie on a horizontal north and south line.

4. Move the coelostat north or south until a beam of sunlight reflected from its mirror falls centrally on the second mirror. Start the clock and clamp the coelostat mirror at this position.

5. Put the lens in place at the central position of its run, which should be at a distance equal to its focal length for $H\alpha$ (about 18 ft.) from the first slit of the spectrohelioscope.

6. Turn the second mirror until the beam of sunlight falls centrally on the lens. The solar image should then be central on the first slit of the spectrohelioscope and the diverging beam from the slit (opened to 0.01 in. or more) should fall centrally on the upper concave mirror. Readjust, if necessary, to insure this coincidence.

7. Look at the solar image on the first slit through a piece of red glass and focus the lens by the screw until a sun-spot or the sun's limb is sharp on a piece of white paper held against the slit jaws.

Spectrohelioscope.—1. Set the casting that carries the slits and grating support with its face vertical and in an east-and-west plane; the axis about which the grating rotates should now be vertical; then fasten the casting firmly in place on the pier.

2. Make certain that the upper slit and the lines of the grating are also vertical.

3. Square up the casting supporting the concave mirrors and fasten it to the pier at the point where the distance of the silvered faces from the slits, at the middle of their run, is about equal to the focal length of the mirrors (about 13 ft.).

4. Incline the upper concave mirror by its adjusting screws until the beam of sunlight is reflected to the center of the grating.

5. Rotate the grating (unclamped) until the direct reflection (not one of the spectra) falls centrally on the lower concave mirror. If necessary tip the grating backward or forward in its cell until this adjustment is correct. Note that the brightest first-order spectrum should now appear on the wall to the right of the mirror. If this is not the case, invert the grating in its cell and readjust.

6. Adjust the lower concave mirror until a direct (white-light) image of the first slit falls exactly on the second or lower slit.

7. Reduce the intensity of the sunlight by means of a dark glass before the first slit and focus the concave mirrors by their screw until the image of the first slit, seen through a positive eyepiece focused on the widely opened jaws of the second slit, is sharply defined.

8. Rotate the grating until the deep red of the brightest first-order spectrum falls centrally on the lower concave mirror. As the grating is rotated the direct reflection and the spectra of the various orders should move along a horizontal line. If they do not, incline the grating in its cell by the side screws until the spectra move horizontally and then check up the other adjustments.

9. Narrow the first slit to a width of about 0.002 inch. The lines of the solar spectrum should now appear through the wide second slit. Refocus the concave mirrors (using a positive eyepiece magnifying ten diameters) until the narrowest lines are perfectly sharp on the slit jaws. The horizontal lines, caused by dust on the first slit, should also be sharp at the same focus.

10. Rotate the grating with the tangent screw until $H\alpha$, the broadest single line in the red, falls on the second slit.

11. Make the width of both the first and second slits 0.004 inch.

12. Put the plane-parallel glass plate (the line-shifter) in place behind the second slit with its face at right angles to the beam, where its circle reading should be zero.

13. Observe the $H\alpha$ line above and below the second slit through the small windows provided for the purpose and bring it into coincidence with the slit by means of the tangent screw of the grating. Rotate the second slit, if necessary, to make it exactly parallel to $H\alpha$.

14. If the spectrum is slightly too low or too high, tip the lower concave mirror by the fine screw provided for vertical adjustment.

15. If oscillating slits are used, move the slit-bar slowly by hand and see whether the $H\alpha$ line moves exactly with the second slit. If not, raise or lower the spectrum by the fine-adjustment screw on the lower concave mirror until line and slit, seen with a 10×-positive eyepiece, move precisely together. After completing these adjustments and checking them by noting (with widened first slit) whether

the beam is still central on both concave mirrors and grating, the instrument should be ready for the observation of prominences and flocculi. Before observing, however, a small screen (about $1\frac{7}{8}$ in. high) should be placed between the grating and the concave mirrors at such a point as to cut off the scattered sunlight which would otherwise be seen if the upper mirror were visible through the second slit. A position can be found where the screen will not intercept the beam between first slit, upper mirror, grating, lower mirror, and second slit.

16. Set the low power ($2\times$) eyepiece opposite the center of the second slit, where the spectra passing through the windows at its extremities are not visible, and focus it sharply on the slit jaws. Run the motor at such a speed as to give a persistent monochromatic image of a portion of the sun about $\frac{1}{4}$ inch wide, sufficiently free from flicker and without troublesome vibration. Turn the line-shifter until the $H\alpha$ line is off the second slit. Move the solar image by the slow-motion cords or rods controlling the second mirror of the coelostat telescope until a sun-spot falls centrally on the first slit. An image of the spot in the red light of the continuous spectrum near $H\alpha$ should then be seen through the second slit and eyepiece. Focus the lens of the coelostat telescope until the spot appears through the eyepiece as black and distinct as possible. Turn the line-shifter back to the zero position, which should bring $H\alpha$ centrally on the second slit, thereby reducing the brightness of the solar image, now due to the hydrogen light of the solar atmosphere. Dark and bright flocculi, resembling those shown in several of the plates, should become visible on the sun's disk, the various parts of which can be examined by moving the solar image. Before studying their details, it is advantageous to become thoroughly familiar with the operation of the instrument by observing the bright prominences projecting beyond the sun's limb.

These can be examined by opening both of the oscillating slits to a width of 0.005 inch or more, and moving the sun's image so as to bring all parts of the circumference successively into the field of view. Select some bright prominence, refocus it as sharply as possible by moving the telescope lens with the screw, and turn the line-shifter. When the $H\alpha$ line moves off the second slit the prominence

naturally disappears. Many prominences differ so slightly in radial velocity in their various parts that they may be equally well seen as a whole at any setting not too far from zero to exclude the bright central region of the $H\alpha$ line. The various types of flocculi, the study of their structure at various levels, and the analysis of "motion forms" due to marked differences of radial velocity are described below.

Anderson's rotating prisms.—When Anderson's rotating prisms are used with fixed slits, the $H\alpha$ line does not oscillate but remains at rest, and adjustment (15) becomes unnecessary. Instead, the following adjustments of the rotating prisms are required:

1. The two prisms (square in cross-section) are mounted in their cells at the ends of a steel shaft turning in bearings attached to a brass base plate. Place this in a beam of direct sunlight broad enough to cover both prisms.

2. Rotate the shaft slowly and watch the rectangular areas of sunlight as reflected successively from the four faces of one prism on a wall at least 10 or 12 feet distant. Mark on the wall the ends of one of these rectangles and fit the prism cell until the ends of the four rectangular reflections correspond in position, indicating that the axis of the prism coincides with the axis of the shaft. (This adjustment is made once for all by filing or scraping the three-point supports against which the prism-cell rests.)

3. Repeat for the second prism.

4. As the faces of the two prisms may not yet lie in the same plane, watch the rectangular areas and rotate one of the prisms until they correspond perfectly.

5. The first and second (fixed) slits of this form of spectrohelioscope are supported by a box casting, as shown in Plate XIV. Each slit is pivoted on a screw, and by releasing two clamping screws (from the rear) the slit may be rotated about its center. (The lower slit is also provided with another motion for lateral adjustment.) Set both slits in a vertical line.

6. Fasten the base plate carrying the shaft and prisms to the box casting, thus bringing one prism in front of each fixed slit.

7. Place the casting in front of a window, not in direct sunlight, with the prisms facing the window. (If the casting is already in posi-

tion on its pier, skylight may be reflected through the prisms with the aid of one or two large mirrors.)

8. Open the slits to a width of about 0.003 inch and look at the upper prism through the first slit from the rear. As the prisms are slowly rotated, their vertical corners can be seen as dark lines, momentarily cutting off part of the light as they pass the slits. If these lines are not exactly parallel to the upper slit, rotate this slit as described above until the light is cut off throughout its whole length at the same instant. Leave the prism in this position.

9. Look through the second or lower slit, and observe the line due to the corners of the lower prism through the small windows above and below the slit. If the coincidence is imperfect, move the slit laterally, or rotate it slightly until the light is cut off from both slits at the same instant when the prisms are turned.

10. Assuming the box casting, with slits and prisms in adjustment, in place on its pier, bring the solar image on to the first slit. Observe a narrow absorption line close to $H\alpha$ and notice that it makes a small angle with the second slit. Remove about half this angle by rotating the first slit and the balance by rotating the second slit. Set $H\alpha$ centrally on the second slit by rotating the grating (the line-shifter is assumed to be set at zero).

Line-shifter.—The line-shifter used on the horizontal spectrohelioscope described above is a plate of plane-parallel glass about 0.06 inch thick, mounted behind the second slit. When $H\alpha$ is set as nearly as possible on the center of the slit by the tangent screw of the grating, this glass plate is supposed to stand at right angles to the beam from the lower concave mirror; at this point the circle of the line-shifter should read zero. In practice, there is usually a slight correction to be applied to the zero reading, readily determined as follows:

1. Set the first and second slits at the widths to be used in observations with the spectrohelioscope (about 0.003 or 0.004 in. for the disk and the brighter prominences beyond the limb, and roughly twice this width for fainter, quiescent prominences). Observe the $H\alpha$ line through the small window above the second slit and rotate the line-shifter to the right until the most perfect coincidence of the slit with the center of the line is seen with an eyepiece or lens magnifying

about ten diameters. Note the circle reading. Repeat by rotating to the left, again noting the reading. Shift the eyepiece and repeat both right and left readings through the lower window. Their mean should obviously be practically the same as that for the top of the slit if line and slit are parallel. The mean of all four readings gives the zero correction for the middle of the slit. (A more precise method, not necessary in practice, would be to use a compound microscope, with filar micrometer, for settings on line and slit.)

TYPES OF HYDROGEN FLOCCULI

Before describing in detail the use of the line-shifter for the comparative study of phenomena at various levels in the solar atmosphere and the velocity analysis of moving gases, a brief statement regarding the types of hydrogen flocculi rendered visible by the spectroheliosope may be of service. I have accordingly selected a number of spectroheliograms from the large collection of the Mount Wilson Observatory, which have been copied by Mr. Ellerman for reproduction, usually on a scale large enough to show the characteristic structure of the fields of force (when present). In this paper I shall describe the principal types of flocculi very briefly, but later some of their peculiarities will be more fully discussed in the light of recent observations with the spectrohelioscope.

The coarser structure of the hydrogen atmosphere, as revealed on spectroheliograms taken with the $H\alpha$ line, is shown in the small-scale photographs reproduced in Plate VII. These represent the 2-inch (52 mm) solar image photographed on Mount Wilson with the 13-foot spectroheliograph. An auxiliary slit, set on the continuous spectrum about $2\frac{1}{4}$ inches (57 mm) from the second slit centered on the $H\alpha$ line, gives a direct image of the photosphere and spots for comparison with the hydrogen image. In most cases the dispersion employed is 0.25 mm per angstrom at the $H\alpha$ line, and, as the second slit is generally 0.1 mm wide, only the central part of the dark line is used for these photographs.

The term "flocculi," which is not always used in the same sense by writers on astrophysics, should be clearly understood. In 1903 I suggested that all objects shown on spectroheliograms of the sun's disk taken with the lines of calcium, hydrogen, or other elements, be

called by this name.[1] In the present paper this designation is employed in harmony with the original definition, which may be quoted here for the sake of clearness:

> The term "flocculi" is applied indiscriminately to all bright or dark clouds of vapor photographed in projection on the sun's disc, without distinction of level. In other words, a flocculus may be a mass of vapor in the reversing layer, or in the chromosphere, or in a prominence. For this reason we shall speak of calcium flocculi, hydrogen flocculi, etc.[2]

The determination of level is not always an easy task, and consequently a general term was adopted.

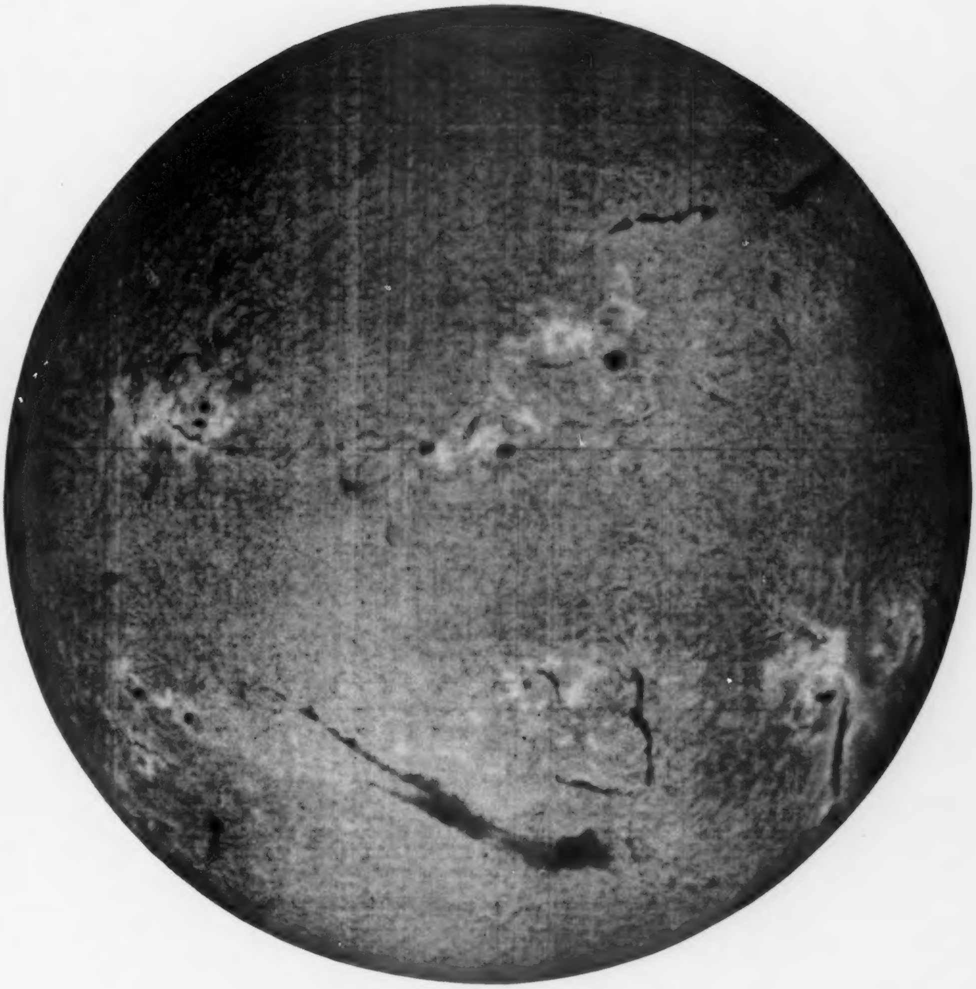
The flocculi photographed with the central part of the $H\alpha$ line are both bright and dark, as represented in Plate VII and other photographs. Bright flocculi are usually found in the spot zones, and are brightest and most conspicuous near the sun's limb and in the immediate vicinity of sun-spots (Plates XV, XVI*a*, and XVII). Quiescent bright flocculi, which change slowly in form, coincide approximately with the faculae and with the low-level bright flocculi photographed with the calcium lines H_1 or K_1. Differences in form are partly due to the absorptive effects of overlying dark flocculi. Active bright flocculi, which are often far brighter than the quiescent ones, change rapidly in form and intensity. They usually appear suddenly, close to active sun-spots, and sometimes become extremely brilliant and spread over large areas. These will be referred to later in a discussion of the use of the spectrohelioscope for the study of the relationship between solar and terrestrial phenomena.

Dark hydrogen flocculi are found on all parts of the disk, not merely in the sun-spot zones but often close to the poles. The more conspicuous ones are usually greatly elongated and have been called by Deslandres "filaments." Most of these represent or are closely associated with prominences, seen in projection on the disk as dark absorbing areas (Plate XVII*a*, *b*, *c*). Objects of this type generally change slowly in form unless they fall within the range of action of the fields of force, where they may often be seen with the spectrohelioscope as they are rapidly drawn into the vortices surrounding sun-spots.

[1] Hale and Ellerman, *Publications of the Yerkes Observatory*, **3**, Part I, 14, 1903; *Astrophysical Journal*, **19**, 42, 1904.

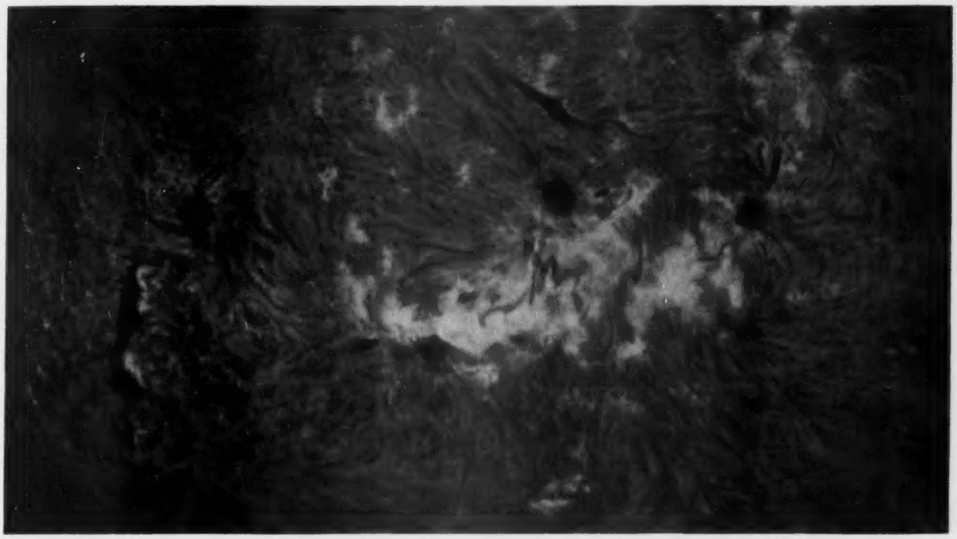
[2] Hale and Ellerman, *Astrophysical Journal*, **19**, 42, 1904.

PLATE XV

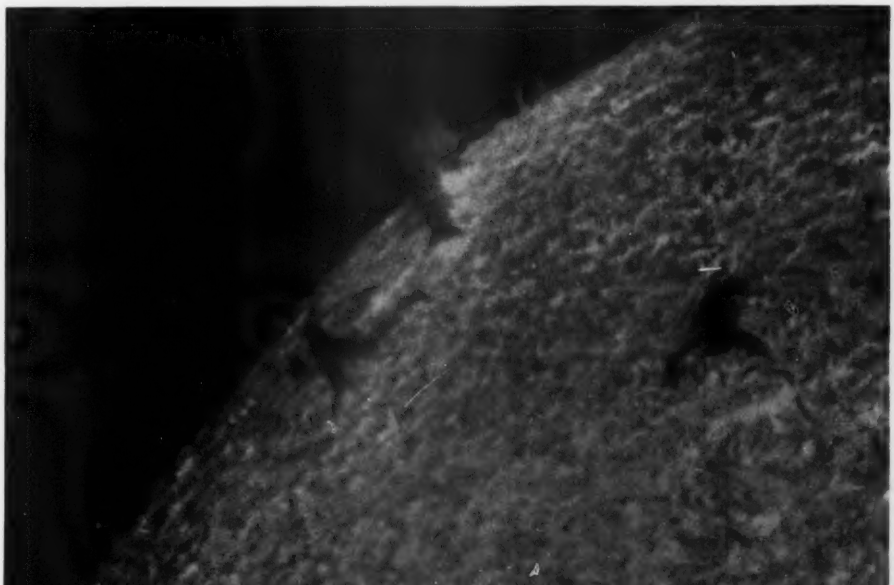


Bright and dark hydrogen flocculi. Enlarged from a small-scale spectroheliogram taken by Lewis Humason on February 17, 1926.

PLATE XVI

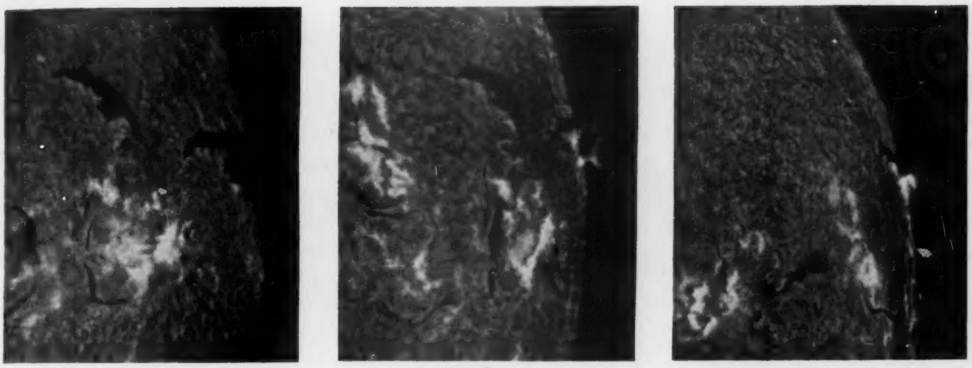


a.—Bright and dark hydrogen flocculi. From a spectroheliogram taken by A. H. Joy on July 11, 1917.



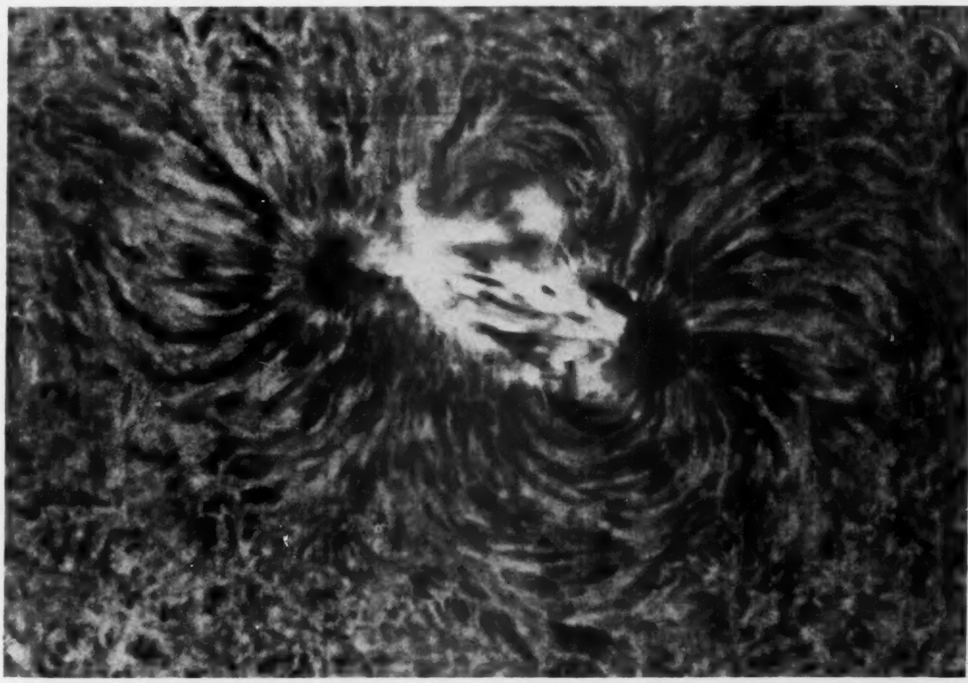
b.—Dark hydrogen flocculus, appearing as a prominence where it projects beyond the limb. From a spectroheliogram taken by S. B. Nicholson on June 16, 1916.

PLATE XVII



a *b* *c*

a, *b*, *c*.—Hydrogen flocculi photographed on three successive days. From spectroheliograms taken by A. H. Joy on June 27, 28, and 30, 1916.



d.—Structure of hydrogen flocculi near large bipolar sun-spot group of August 30, 1924. From a spectroheliogram by Lewis Humason.

Active as well as quiescent dark flocculi are frequently observed, as would be expected from our knowledge of eruptive prominences. Many of them fail to appear as a whole on spectroheliograms because of their great radial velocity, which may displace parts of the $H\alpha$ line to red or violet by an angstrom or more, and thus throw them off the second slit. Such flocculi are easily observed, however, with the spectrohelioscope and line-shifter, especially in association with active bright flocculi, from which they often rise as jets and arches. They sometimes develop suddenly near sun-spots, where their behavior gives valuable information regarding the nature of the fields of force.

It should be noted here that the distinction between bright and dark flocculi is somewhat arbitrary, as some flocculi that appear dark near the center of the sun would probably appear bright near the limb. Moreover, the hydrogen rising from bright flocculi often turns dark at a higher level.

The most interesting and perhaps the most significant structure in the solar atmosphere is that shown by the configuration of the dark hydrogen flocculi near sun-spots (Plates XVII*d*, XVIII*a*, and XIX). When this structure was first detected on Mount Wilson in 1908 I ascribed it to the stream lines of extensive hydrodynamical vortices,[1] but subsequently Störmer investigated the hypothesis that it represented the lines of force of the magnetic fields in sun-spots.[2] The study of certain details of this structure with the spectrohelioscope is described below (p. 299).

HYDROGEN FLOCCULI AT VARIOUS LEVELS

The foregoing remarks apply to flocculi as shown by the spectroheliograph or spectrohelioscope with the second slit set centrally on the $H\alpha$ line. It was long ago recognized, however, both by Deslandres and myself, that cross-sections of the solar atmosphere at various levels may be photographed by setting the second slit of the spectroheliograph at different distances from the center of the calcium and hydrogen lines. This conclusion has been fully confirmed by the work of Adams, Evershed, St. John, and others, and recently

[1] *Mt. Wilson Contr.*, No. 26; *Astrophysical Journal*, **28**, 100, 1908.

[2] *Mt. Wilson Contr.*, No. 109; *Astrophysical Journal*, **43**, 347, 1916.

by Unsöld[1] on the basis of modern physical theory, in which the old conception of pressures of several atmospheres, increasing with the depth, has been abandoned. Very high dispersion, as pointed out in 1903,[2] and subsequently applied with admirable results by Deslandres and D'Azambuja,[3] is needed to isolate completely the H_3 or K_3 lines of calcium, which record the high-level dark calcium flocculi shown for the first time, with less contrast, on photographs taken with the lower dispersion of the Rumford spectroheliograph at the Yerkes Observatory.

The method described in the foregoing papers is illustrated in Plate XVIII*b*, *c*, *d*, *e*, *f*, which reproduces a series of photographs of the same region of the sun taken by my assistant, Mr. Hitchcock, with the 13-foot spectroheliograph of my Solar Laboratory in Pasadena on August 29, 1929. This instrument, which is described below (p. 306), is similar optically to the spectrohelioscope used in conjunction with it. Like the spectrohelioscope, it is provided with a line-shifter, and as the photographs were taken at settings of 0 ($H\alpha$ central on the second slit), -6, -10, -16, and -21, the structure shown at the decreasing levels is just what one would observe visually with the spectrohelioscope if its line-shifter (assuming the glass plate to be of the same thickness in both cases) were set at the same circle readings. As the flocculi in question were of the quiescent type, characterized by slow changes in form and small radial velocities, this illustration will serve to indicate the differences of structure, due chiefly to differences in level, which are very unlike those observed in active regions, marked by varying forms and high velocities, changing rapidly with time and from point to point at any given instant.

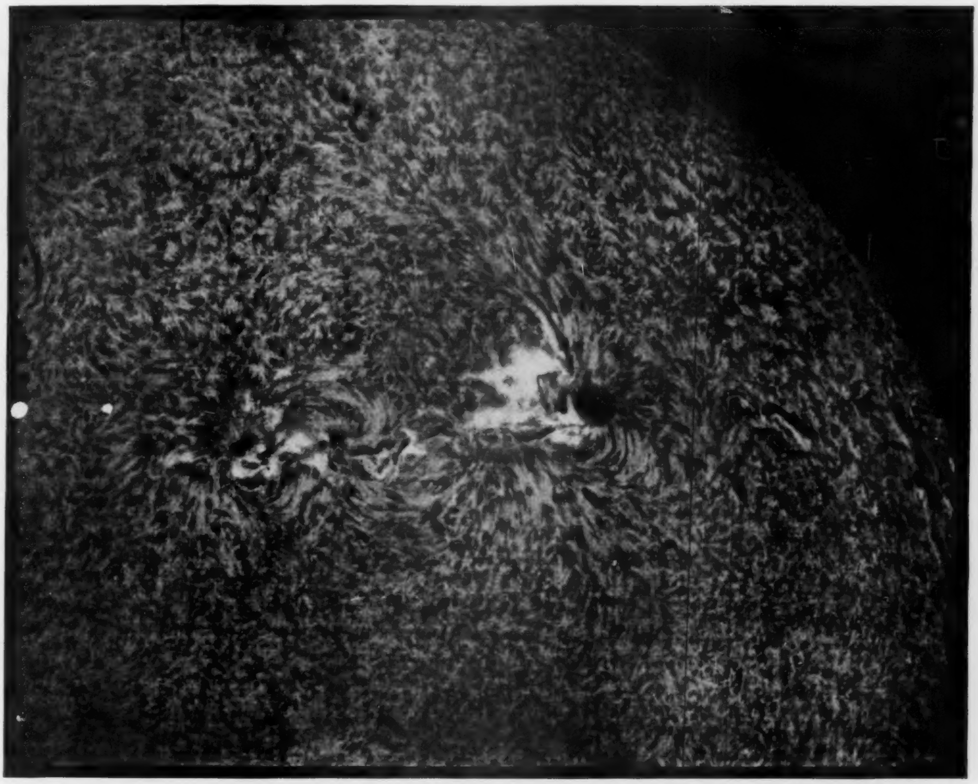
In cases of this kind, where the movements in the solar atmosphere are too gradual to produce important modifications of structure during the intervals involved, the spectroheliograph has the advantage of giving a permanent record for preservation and study. It often happens, however, that a far quicker and more flexible mode

[1] *Mt. Wilson Contr.*, No. 378; *Astrophysical Journal*, **69**, 275, 1929.

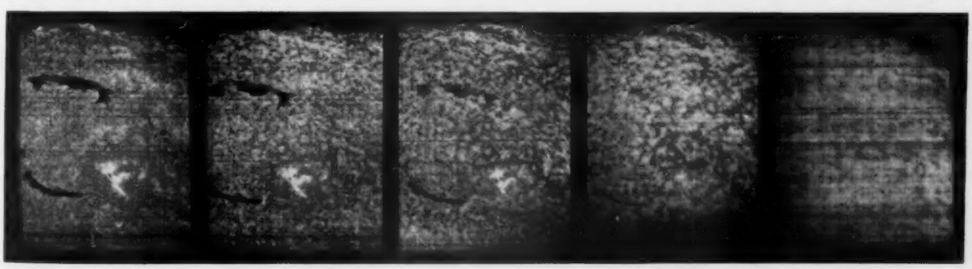
[2] Hale and Ellerman, *Yerkes Observatory Publications*, **3**, Part I, 17–19, 1903; *Astrophysical Journal*, **19**, 48, 1904.

[3] *Annales de l'Observatoire de Meudon*, **4**, 1910.

PLATE XVIII



a.—Structure of hydrogen flocculi near sun-spots. From a spectroheliogram taken by Ferdinand Ellerman on January 5, 1917.



b (0, center of $H\alpha$) *c* (−6) *d* (−10) *e* (−16) *f* (−20)

b, c, d, e, f.—Same region of sun, as photographed by Hitchcock at center of $H\alpha$ (*b*) and at increasing distances toward the violet.

PLATE XIX

a.—Hydrogen flocculi surrounding the southern bipolar spot-group, Mt. Wilson No. 2656. Both vortices showed clockwise inflow, as illustrated for the preceding spot in (*b*). From a spectroheliogram taken by Ellerman on August 15, 1926.

b.—Acceleration of the radial velocity of the inflowing hydrogen, shown by the line-shifter of the spectrohelioscope.

of comparison is necessary to assure the recognition of phenomena otherwise certain to be overlooked or misinterpreted. The total exposure time for the five photographs reproduced in Plate XVIII was 25 minutes, making no allowance for the intervening instrumental adjustments.[1] With the spectroheliscope the solar atmosphere at all of these levels and other intermediate ones, from the photosphere to the highest region attained by hydrogen, can be rapidly passed in review by a single quick turn of the line-shifter. Moreover, its adjustable stops permit the structure corresponding to any two levels to be instantly compared with the well-known precision of the Zeiss "blink"-micrometer and stereocomparator. By this method, or (less completely) by the use of two second slits (p. 283), we have the simplest and quickest means of detecting the relationship of the flocculi at any level to neighboring sun-spots.

I need not dwell at present on the structure of the flocculi at different heights, as this will appear more clearly in subsequent descriptions of particular cases.

ANALYSIS OF "MOTION FORMS"

The term "motion forms" is due to Lockyer, who first observed the distortion of the hydrogen lines in prominences and near sun-spots in 1869. His paper[2] and its addendum describe and illustrate reversed lines on the disk, the distortion of the $H\beta$ (F) in a prominence caused by cyclonic motion, and the varying appearances of this line in the following part of a long train of spots. In some places it disappeared entirely, or appeared as a bright line, at times greatly widened toward red and violet ("lozenges"), again widening only on one side, again as a widened bright line bounded on its red side by a dark line. Such distortions, which may assume fantastic shapes in striking contrast with the customary straight lines characteristic of a narrow slit, Lockyer named "motion forms." Symmetrical widening ("lozenges") he attributed to increased pressure, while the irregular displacements were ascribed to motion of the gas toward or from the earth. Even at this late date in solar spectroscopy, when

[1] Faster plates (giving less contrast) are now available.

[2] *Proceedings of the Royal Society*, 17, 415, 1869. Reprinted in Lockyer's *Contributions to Solar Physics*, p. 488, where quotations on this subject from the papers of Young, Secchi, Rayet, Respighi, and others may also be found.

applying the new principles of modern physics, it is well worth while to re-read these early observations and those of Young, Secchi, Respighi, Rayet, Tacchini, Vogel, Zöllner, and others who took part in the spirited discussions of the period.

The introduction of photographic methods of recording solar spectroscopic phenomena was attended by many great advantages and some disadvantages. Rutherfurd and Rowland concentrated their attention on the spectrum of sunlight as a whole and made no attempt to deal with such localized phenomena as spots, faculae, or prominences. When these were attacked photographically in the early nineties, the new work absorbed so much time and attention that visual observations were somewhat neglected by those involved in it. Fortunately, however, the visual record of prominences and certain other solar phenomena has been maintained unbroken by observers in many countries. There is thus a large amount of literature open to those whose interest in the sun has recently been stimulated by advances in physics and chemistry.

The chief disadvantage of photography is that one proceeds more or less mechanically, making exposures without sufficient knowledge of the appearance of the flocculi at the moment, their exact position on the sun, or the critical periods of intense activity that characterize the most interesting phenomena. In work with the spectrograph, even if the slit is first set visually exactly at the points where line distortions are seen, their rapid changes in form, small size, and the effect of bad seeing in rendering them diffuse or causing them to oscillate across or along the slit may prevent the correct registration of their radial velocities. Some drawings by Young, showing the variation in form of the distorted $H\alpha$ line within a few minutes at the western edge of the penumbra of a large spot on September 22, 1870[1], indicate their rapid changes. But the best way to convince one's self of the value of the spectrohelioscope in analyzing such phenomena is to observe them simultaneously with this instrument and with a spectroscope, the narrow slit of which is set at the same position on the sun. The method I employ for this purpose is described on page 309.

[1] *Journal of the Franklin Institute*, 60, 338, 1870. Reproduced in Lockyer's *Solar Physics*, Fig. 173, p. 600.

I am not attempting to prove that the spectrohelioscope can take the place of the spectrograph, which gives measures of higher precision of such small line displacements as those due, for example, to the comparatively slow ascent or descent of gases in the solar atmosphere; nor does it compete with the velocity spectrograph, in the kind of work for which the latter is best adapted. The true function of the spectrohelioscope is to supplement these instruments, and also the spectroheliograph, not only by revealing many phenomena that would otherwise escape detection, but especially by the method of velocity analysis described below.

A motion form observed by myself in the great sun-spot group of February, 1892, shortly after the first photographs of calcium flocculi had been made with the Kenwood spectroheliograph, will serve to illustrate my meaning. The drawing reproduced in my paper shows a curved branch of $H\alpha$, extending toward the red and then bending downward to meet the dark absorption band caused by one of the spots of the group. It lasted only a few minutes, and I inferred that I was observing a varying mass of absorbing hydrogen, one extremity of which showed zero radial velocity while the other was moving rapidly downward toward the spot.[1] But I had no adequate means of determining its form or of studying its changes, both of which a spectrohelioscope would have supplied. Contrast this with some observations made with the latter instrument on August 15, 1926.

While examining the vortex structure associated with the large spot group then near the central meridian of the sun I noticed among other phenomena two slender, curved flocculi, both of which changed in appearance as the line-shifter was rocked back and forth. As the light in which they were observed varied in wave-length, the resulting effect was a shift of the position of maximum intensity along the curved flocculi. In fact, their dark heads were seen to advance toward the spot as the $H\alpha$ line moved across the second slit from its center toward the red. At a slit position completely outside of $H\alpha$ the curved flocculi had disappeared, but their extremities, like small black dots, were still visible, projected against the outer boundary of

[1] Hale, *Astronomy and Astrophysics*, 11, 314, 1892; Crew, *ibid.*, p. 309.

the penumbra. Another slender flocculus south of the preceding spot behaved in the same way.

Before giving the quantitative visual analysis of these effects, completed a few minutes later, let us consider how phenomena of this kind could be detected and interpreted in other ways. The spot in question was the preceding member of a bipolar group (Mount Wilson, No. 2656) at 18° south latitude, then about 4° east of the central meridian. The 75-foot spectrograph of the 150-foot tower telescope on Mount Wilson showed it to be of north magnetic polarity, with a field strength on that day of 2800 gausses. The following spot was of south polarity, with a field strength of 2500 gausses. A direct photograph of the group was taken on Mount Wilson the same morning with the 60-foot tower telescope. From this, of course, no knowledge regarding the phenomena in the hydrogen atmosphere about the group could be derived, but it was useful in making the drawing (Plate XIX*b*) showing the outline of the spots.

Two methods of observation other than the use of the spectrohelioscope might be employed in studying the flocculi associated with these spots. A series of photographs of the spectrum, taken at various points in the group, might register certain small projections from the $H\alpha$ line, of varying form and length, in case the slit happened to lie in the right positions across the curved flocculi and also provided these slender objects were of sufficient width and intensity to appear on the negative, under the conditions imposed by the size of solar image, effects of vibration due to wind or other mechanical disturbances, the quality of the atmosphere, and the linear dispersion employed. Even if clearly registered, the measurement and interpretation of these motion forms would be a slow and tedious process.

On the other hand, a spectroheliograph might be employed to reveal the flocculi. My own spectroheliograph in Pasadena was not then ready for use, but I am fortunately able to give an enlargement of a photograph of the group (Plate XIX*a*) made the same morning by Ellerman with the 13-foot spectroheliograph of the 60-foot tower telescope, which shows the curved flocculi and other structure in the hydrogen atmosphere. The slit was set at the center of $H\alpha$, but if Ellerman had known what phenomena were in progress and the posi-

tions of the second slit required to register them, he might have obtained photographs of the effects described below; assuming, of course, that the demands of the various other solar observations of the daily program gave him time to do so. As it is, the spectroheliogram is of great value in showing the general structure of the field of force surrounding the spot group much more completely and accurately than I could have drawn it. The photograph also suggests the fact, proved beyond question by the spectrohelioscope, that the curved flocculi adjoining two spots marked by intense magnetic fields of opposite polarity both showed clockwise inflow—a point of prime importance in the interpretation of the nature of the forces in operation.

We may now turn to my visual work with the spectrohelioscope, in which the beautiful details of the $H\alpha$ flocculi were clearly seen, in spite of the fact that the atmospheric conditions in Pasadena were decidedly inferior to those a mile above me on Mount Wilson. One of these details, the curved flocculus shown in the sketch (Plate XIX*b*), which was more intense than the others in the same region, was selected for observation. When the circle of the line-shifter indicated a radial velocity of +22 km/sec., only the outer part of the flocculus (*A* in Plate XIX*b*) was visible. As the line was displaced farther to the violet, the flocculus seemed to move from *A* to *B*, the portion *B* corresponding to a velocity of +45 km/sec. When the second slit was about 1.1 A to the red of the center of $H\alpha$, corresponding to a velocity of about +50 km/sec., nothing remained visible of the flocculus except the black dot *C*, which was precisely on the edge of the penumbra. At still greater displacements the dot faded away and finally disappeared. The apparent advance of the flocculus toward the spot and the disappearance of all but the head were observed as often as the $H\alpha$ line was moved across the second slit from violet toward red.

It is interesting to note the accelerating radial velocities indicated by the successive slit positions, increasing from 22 km/sec. at a distance of 56,000 km from the center of the spot (*A*) to 45 km/sec. at a distance of 36,000 km (*B*) to about 50 km/sec. for a distance of 20,000 km, corresponding to the dot marking the inner extremity of the flocculus exactly on the outer edge of the penumbra (*C*). These

values are not of the highest precision, but they cannot be far from the truth.

We at once recall the flow of prominences toward sun-spots,[1] as photographed in elevation at the sun's limb by Slocum with the Rumford spectroheliograph. Another series of calcium spectroheliograms of the prominences surrounding a large spot at the sun's limb on October 8, 1910, is also reproduced in his article on "The Attraction of Sun-Spots for Prominences."[2] Slocum directs attention to three bright knots on a long streamer, which gave velocities along the apparent trajectory of 16, 20, and 60 km/sec. at distances of 170,000, 130,000, and 75,000 km from the center of attraction. Pettit, who remeasured these plates, got velocities of 5, 8, and 44 km/sec., respectively. From these and other measures Pettit concludes: "Normally the matter about the spot is moving into it with accelerated velocities averaging about 35 km per second, sometimes reaching 100 km per second." Both Slocum and Pettit found that jets may be projected away from a spot at similar velocities, but Pettit[3] does not consider them to represent the normal condition. Evershed, on the contrary, in discussing his Kodaikanal observations of prominences, says: "No case has been found in which prominences were falling into sun-spots, but the reverse has several times been observed."[4] The difficulties involved are sufficiently indicated by these differences in opinion among experienced observers, but fortunately most of them are removed by the spectrohelioscope, in so far as the determination of the direction of flow and the radial velocity are concerned.

It is evident, however, that the observed radial velocity must depend upon the actual velocity along the true trajectory and the angle between this trajectory and the line of sight. If the trajectory is

[1] It should be clearly understood, however, that Slocum's photographs represent three successive stages in the inflow of the tip of a prominence, whereas in the case illustrated in Plate XIX the tip had already reached a point above the edge of the penumbra before the observations were begun. With a rather wide second slit, nearly the whole length of this curved flocculus (*A–C*) could be recorded in a single photograph, as shown in Plate XIX*b*.

[2] *Astrophysical Journal*, **36**, 265, 1912.

[3] *Publications of the Yerkes Observatory*, **3**, Part IV, 1925.

[4] *Memoirs of the Kodaikanal Observatory*, **1**, Part II, 106, 1917.

parallel to the solar surface, and the spot, as in the present case, is near the center of the sun, there will be no displacement of $H\alpha$, and the entire flocculus will be visible when the second slit of the spectroheliscope is set on the center of the line. Judged from the characteristic forms of prominences at the sun's limb, this is usually the condition of affairs at a considerable distance from a spot, though it often happens that at such a point the hydrogen is rising rapidly from below, thus producing a marked displacement of $H\alpha$ toward the violet when observed near the center of the sun. Nearer the spot, as the prominences at the limb discussed by Slocum and Pettit indicate, the trajectory makes an angle with the sun's surface ranging from small values up to 45° or even more. At the limb, the projection of the trajectory is often nearly a straight line over a great part of its length, and the increase in the radial component of the velocity observed on the disk as the spot is approached is probably due chiefly to the acceleration found by Slocum and Pettit. Sometimes, however, their limb photographs show that the tip of the inflowing prominence turns down close to the spot, and in spectroheliscopic observations made near the center of the disk this might account in such cases for an increase in the radial component of the velocity at this point, without a corresponding increase in the acceleration along the trajectory.

The curved flocculus shown in Plate XIX probably represents a prominence of moderate height projected against the disk. If we assume the trajectory to make an angle of 30° with the sun's surface, the corresponding velocities along the trajectory would be 44 km/sec. for the outer part of the flocculus (A), 90 km/sec. for the central part (B), and about 100 km/sec. for the tip (C).

The observation of August 15, 1926, proved to be typical, and it has been repeated in scores of cases, many of which will be described in detail in a later paper, where the bearing of these results on the work of St. John, Evershed, Fényi, Slocum, Pettit, and others will be discussed. In the present article I wish merely to make clear this new method of observation, in which the visibility of an object emitting approximately monochromatic light depends upon its radial velocity. The method evidently affords a valuable means of analysis, not merely of the hydrogen whirls but also of other important phe-

nomena of the solar atmosphere. Noteworthy among these are the eruptive dark arches often seen with the spectrohelioscope. The following observation will suffice to show their nature.

On May 31, 1926, while observing spot No. 2571 (8° S., 20° E.) with the spectrohelioscope, I noticed a curious dark arch following the spot. The preceding end of this arch, which was seen when the second slit was on the violet side of $H\alpha$, seemed to rise from a small bright flocculus a short distance east of the spot. The central part of the arch, farther to the east, appeared when the slit was near the center of $H\alpha$, but its eastern extremity, where it seemed to curve back toward the surface of the sun, did not become visible until the slit was well beyond the boundary of $H\alpha$ toward the red. Obviously we have here a dark arched prominence, rising with high velocity from a bright source near the sun-spot, pursuing a curved trajectory, the central part of which was nearly normal to the line of sight, and falling with high velocity at a point well to the east of its origin.

Since that date I have observed many of these arches and followed them across the disk until they were seen as high looped prominences projecting beyond the limb. They usually change rapidly in form and intensity but may be frequently renewed, sometimes from one point, again from another. In a bipolar spot-group three or four may often be seen at once, rising from a region of bright flocculi (such as that shown between the spots in Plate XIX*a*) and falling at a distance, sometimes on the penumbra of one of the spots, sometimes elsewhere. When the radial velocities are high and the oscillating slits narrow, only a short section of an arch may be visible at a given position of the second slit on $H\alpha$. To show the whole arch, the line-shifter must be employed. As the line moves across the slit from violet to red, the maximum of intensity may be seen rising from the source of the ascending branch, passing along the trajectory, and running down the descending branch, which often seems to terminate in a rather definite dark head. The effect is of course different in different parts of the sun, because it depends upon the angle between the true trajectory and the line of sight. The appearance of such arches at the limb is illustrated in drawings by Young and others, and in many spectroheliograms. These looped prominences

often appear intensely bright, even with the narrow slits of the spectrohelioscope employed for observations of the disk.

Another type of flocculus best observed with the spectrohelioscope is that which appears suddenly as a dark mass near large spots, often those of the bipolar type. If the spot group is near the center of the sun, the radial component of the ascending gas may be so great as to displace the hydrogen line an angstrom or more to the violet, thus completely excluding such flocculi from spectroheliograms taken with the second slit set at the normal position of $H\alpha$. As the line-shifter is turned from red to violet, these eruptive masses may be picked up visually and then watched as they are sucked toward the spots. I have observed very striking examples of this kind, which appeared about midway between the principal members of a bipolar group, at a considerable distance to one side of the line joining them. It is a fascinating sight to follow the disintegration of the flocculus and to trace the paths of its fragments as they are drawn asunder toward the two attracting centers. Some cases of this kind will be described in a later paper.

These applications of the spectrohelioscope will suffice to illustrate its advantages over the spectroheliograph when rapidly moving objects are under examination. Although I long ago recognized certain arches among the $H\alpha$ flocculi on spectroheliograms, and studied them by stereoscopic and other means in 1925, I could only suppose, but not prove, that the "bar magnet" structure of the fields of force might be due in part to them. In this study I made use of a series of spectroheliograms taken simultaneously with the second slit set on the red and violet sides of $H\alpha$, and inferred that their differences might be caused by motion of the gas along the arch. More can be learned in a few minutes, however, from such visual observations as I have just cited than from the comparison of many spectroheliograms, unless these are taken with the spectrohelioscope as a guide.

A word of caution regarding the use of the line-shifter for the study of moving gases should be added. In general, the chief criterion for distinguishing between effects due to differences in level and differences in velocity lies in comparing the structure and intensity of the flocculi on the red and violet sides of $H\alpha$. If at equal distances

from the center of the line they differ materially, the asymmetry is probably due chiefly to the radial velocity of the gas, though other possible causes of asymmetry should not be forgotten. The most useful velocity effects are those of the progressive character just described, where the maximum of intensity runs along a flocculus, usually of the slender, curved type. It should be carefully noted in such cases, however, whether the observed displacement of the maximum of intensity with change of wave-length advances progressively from violet to red or whether, as occasionally happens, certain parts of a flocculus show maxima on both sides of $H\alpha$. The latter phenomenon is sometimes seen in (dark) eruptive flocculi, characterized by great widening of $H\alpha$ and by strengthening of its outer wings. Some cases of this sort will be described in a later paper.

ZEEMAN AND STARK EFFECTS

Imagine a Zeeman triplet, observed in the spectrum of a spark between the poles of a magnet. Along the lines of force only the two outer components of the triplet, circularly polarized in opposite directions, are visible. A quarter-wave plate and nicol, when properly adjusted, will quench either component. If the observation is made with a spectrohelioscope, an image of the spark will be seen in the light of the transmitted component, assuming it to be set on the second slit. If the quarter-wave plate is steadily rotated, this image will alternately appear and disappear.

It would be easy to devise a spectrohelioscope having a single first slit and two synchronous second slits that could be set at any reasonable separation in the spectrum. In this way the relative behavior in various parts of a spark or arc of the components of any two lines could be observed simultaneously with the aid of suitable polarizing apparatus and a compound eyepiece, bringing the monochromatic images due to the two lines into opposite halves of the same field of view. Various modifications of the arrangement, adapted for use at any angle with the lines of force, will suggest themselves to the reader. It is possible that such a substitution of a polarized image of the spark, visual or photographic, for the narrow spectral lines ordinarily observed, would assist in detecting slight variations of relative

intensity otherwise likely to be overlooked. The same device might also be used, especially with a Lo Surdo tube, in certain laboratory studies of the Stark effect.

I am in doubt whether this method, even if applied with very high dispersion, can be used in the study of the magnetic fields of sun-spots or the general magnetic field of the sun.[1] In the former case, the general absorption in the spot and the weakness of the field just outside the penumbra and also in invisible spots may prevent tangible results. The weakness of the general magnetic field of the sun is also a serious obstacle. Moreover, the faintness of grating spectra of the highest dispersion, the comparatively low dispersion of prisms in the red, and the large scale of the solar image required stand in the way of success.

On the working hypothesis that appreciable electric fields, ordinarily too weak for detection in the solar atmosphere, might conceivably occur during certain stages of violent eruptive phenomena, I have frequently searched for them with the spectrohelioscope in active prominences and eruptive bright and dark flocculi. Assuming the electric field to be radial, the flocculi were usually observed near the sun's limb, with a nicol and half-wave plate, supported before the first slit. Sometimes a circular half-wave plate, rotated at any desired speed by an electric motor, was employed. In other cases I used a compound half-wave plate, made of narrow strips of mica. By moving this back and forth across the flocculus very slight differences in intensity could have been detected. The line-shifter was set so as to bring one of the outer edges of the greatly widened $H\alpha$ line upon the second slit.

While I have never been able to detect any differences of intensity clearly due to polarization effects, I believe that more observations should be made in this way. The phenomena of asymmetry in $H\alpha$ recently pointed out by Stark should also be borne in mind in these and other observations of the flocculi with the line-shifter.

It is evident that a spectrohelioscope with oscillating slits, rather than one having fixed slits with rotating prisms before them, should

[1] Hale, *Mt. Wilson Communication*, No. 97; *National Academy of Sciences Proceedings*, **12**, 286, 1926.

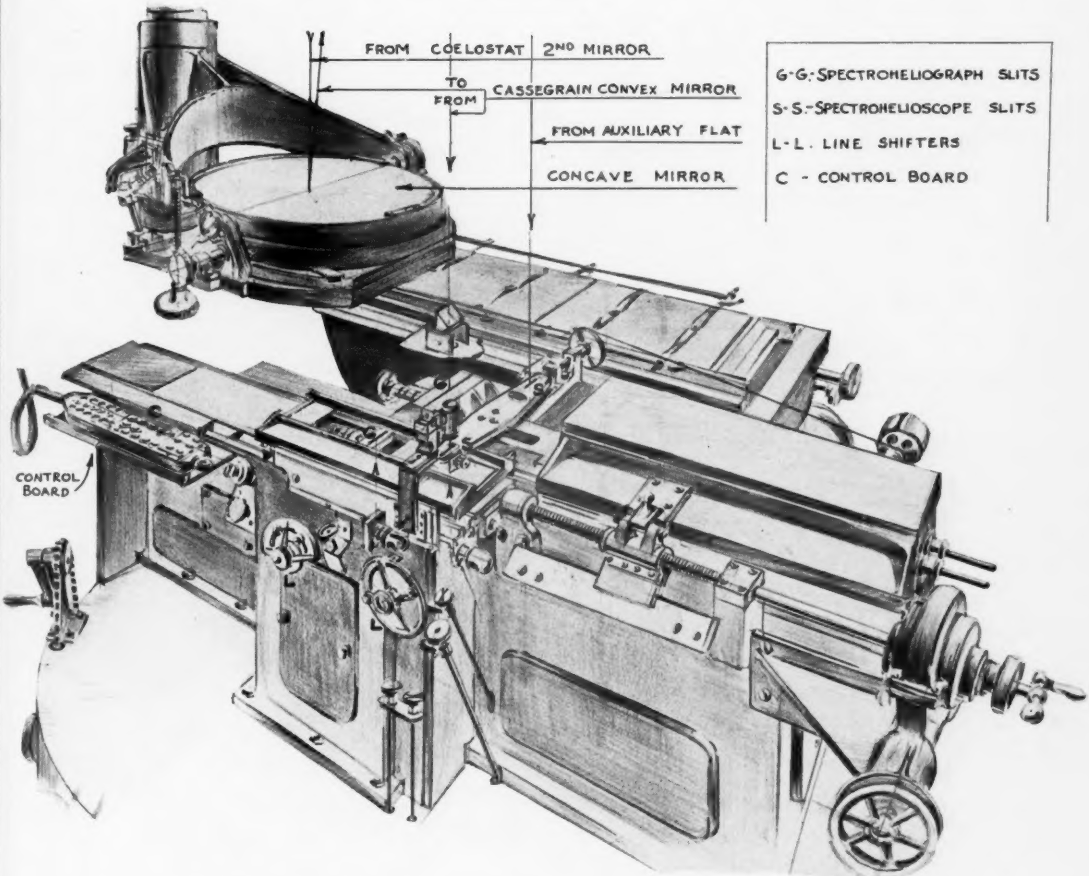
be employed in work of this kind, and that the polarization produced by the grating should not be overlooked.

COMBINATION OF SPECTROGRAPH, SPECTROHELIOGRAPH, AND SPECTROHELIOSCOPE

A spectrohelioscope could easily be adapted to the photography of limited areas of the solar atmosphere; in fact, we have built and tested a special camera attachment for this purpose. But without the finest conditions of seeing and perfect fixity of the solar image during exposures, the results are inferior to those obtainable with a spectroheliograph, which also covers a much larger field. From the visual observations just cited, however, it is evident that a spectrohelioscope can be advantageously used as a guide to photography with a spectrograph or a spectroheliograph, as it reveals the position on the sun of the most interesting phenomena, the moments of active and significant changes, and the wave-lengths at which the second slit of the spectroheliograph must be set to record portions of flocculi or prominences moving with high radial velocities. I have therefore combined the two instruments in my Solar Laboratory, where the spectrohelioscope may also be used in conjunction with spectrographs of from 13 to 75 feet focal length.

The sunlight reflected from the $17\frac{1}{2}$-inch coelostat mirror to the second mirror (also of $17\frac{1}{2}$-in. aperture) at the summit of the low tower of my Solar Laboratory is sent vertically downward to the mirrors or lenses used to form solar images of diameters ranging from 2 to $16\frac{1}{2}$ inches. In simultaneous work with the spectrograph or spectroheliograph and the spectrohelioscope the greater part of this beam falls on the large concave mirror on the left in Plate XX, which is from a drawing by Porter of the combined instruments at the head of the 75-foot spectrograph well in the basement beneath the tower. This mirror returns the now converging rays to a convex mirror of fused quartz, which again reflects them downward to form a large solar image on the first slit of the spectrograph or spectroheliograph. Another portion of the same parallel beam is deflected by two plane mirrors in the tower to a single 6-inch lens of 18 feet focal length, which forms a 2-inch solar image on the first slit of the spectrohelioscope. The adjustments are such that when a given point on the

PLATE XX



COMBINED SPECTROGRAPH, SPECTROHELIOGRAPH, AND SPECTROHELIOSCOPE

larger image is central on the slit of the spectrograph the same point on the smaller image is centered in the field of the spectrohelioscope. This adjustment remains good for all parts of the sun, because both images are moved at the same angular rate by the electric motors that control the position of the second mirror of the coelostat telescope.[1]

As arranged in Plate XX, the spectroheliograph is merely a reflecting spectrograph of 13 feet focal length, with a right-angle prism mounted above its fixed first slit (G_1, beneath the prism), while its second slit (G_2) is also fixed in position during an exposure. The motion of the photographic plate across the second slit is produced by means of a screw driven by an electric motor (on a separate pier), while a lever (not shown in the drawing) connected with the plate-carriage moves the right-angle prism across the first slit at half the speed of the plate. This is a simple and effective device, giving $H\alpha$ spectroheliograms of excellent contrast. In the present arrangement I have purposely restricted the area photographed to $1\frac{1}{4}\times 2$ inches, though it can easily be increased to include a larger field. This is unnecessary in my case, because of the spectroheliographs in use daily for this purpose on Mount Wilson, and the fact that most of my present photographic records are confined to limited regions of a $3\frac{1}{2}$-inch solar image given by a mirror system not mentioned above.

The oscillating slits (S_1, S_2) of the spectrohelioscope, with their driving mechanism, are seen at the right of the spectroheliograph slits (G_1, G_2). The eyepiece[2] used for observing the spectrohelioscope image is in place above the second slit (S_2), and the dials of the two line-shifters (L_1, L_2) are also shown below. A microscope with micrometer eyepiece is used for setting the spectroheliograph slit G_2 on the center of $H\alpha$, after which the line-shifter L_1 of the spectroheliograph is employed in harmony with the indications regarding the most suitable wave-lengths afforded by the visual use of the spectrohelioscope and the line-shifter L_2. The control board for the electric slow

[1] This precise correspondence of the two solar images is required only in the simultaneous use of the spectrograph and spectrohelioscope, as described on p. 309. It is of course affected by the introduction of the moving right-angle prism of the spectroheliograph.

[2] A periscopic eyepiece, permitting the observer to look horizontally while sitting in a chair, will also be available.

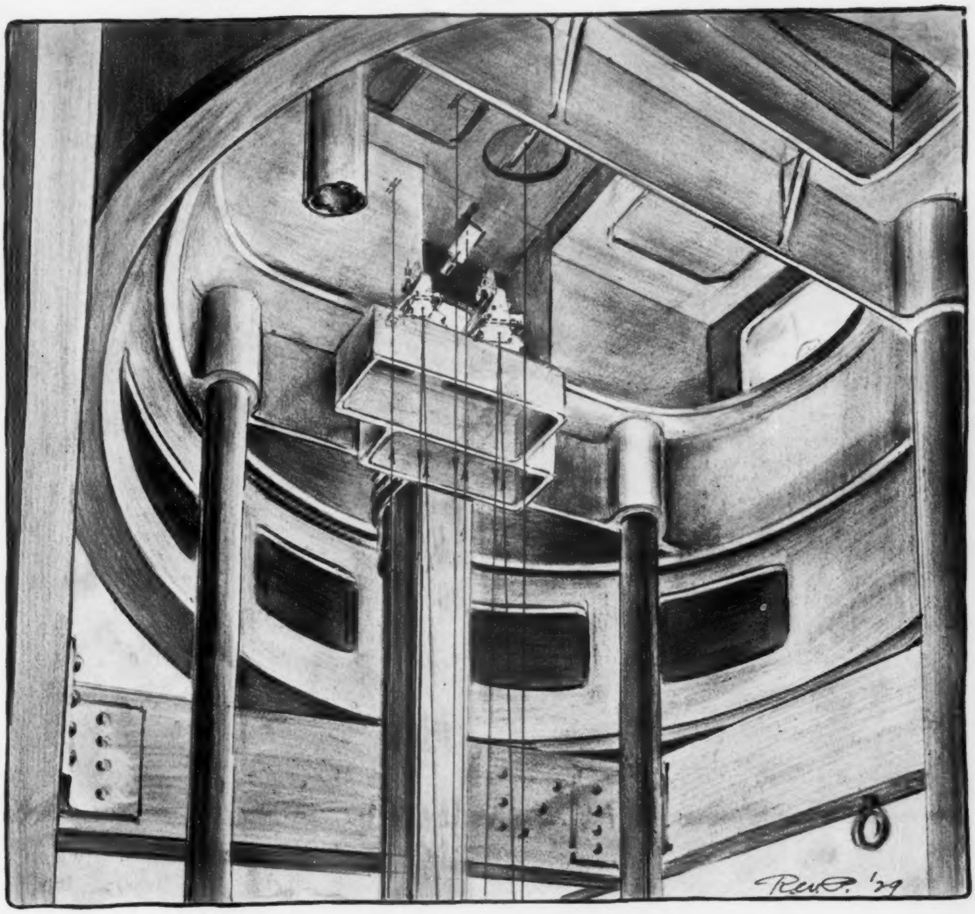
motions appears at the left, while the long plate-holder for photographing spectra of high dispersion with the 75-foot (Littrow) spectrograph is shown beyond the slits.

As for the optical arrangements within the well, only a brief description is needed here to supplement Porter's admirable drawings (Plates XXI and XXII). The slits, gratings, and line-shifter of the spectroheliograph are indicated from below in Plate XXI, which shows the skeleton tube of the 75-foot spectrograph descending toward the bottom of the well from the 5-foot circular casting at the top. The solar rays diverging from the first slits meet the concave mirrors of 13 feet focal length (Plate XXII), which render them parallel and return them to two plane gratings mounted below the circular casting (Plate XXI). These send the $H\alpha$ region back to the second pair of concave mirrors shown in Plate XXII, which form images of the $H\alpha$ line on the second slits of the spectroheliograph and spectrohelioscope, respectively, after passing through the parallel glass plates of the two line-shifters, only one of which is shown in Plate XXI.

The spectroheliograph mirrors can be easily moved out of the way when it is desired to use greater linear dispersion. A pair of similar mirrors of 30 feet focal length can be employed at a lower level in their stead, or the light from the first slit can be sent to the 6-inch lens of 75 feet focal length, with large grating below it at the bottom of the well, which is chiefly used for the study of sun-spot spectra and the general magnetic field of the sun. The spectrohelioscope with its 2-inch solar image is also adapted for use in conjunction with this high dispersion spectrograph, for which a convex mirror in the tower above provides a solar image $16\frac{1}{2}$ inches in diameter. Thus this combined equipment gives solar images and dispersions corresponding with those obtained on Mount Wilson with both the 60- and 150-foot tower telescopes, with the added facilities of the spectrohelioscope and the provision of a $3\frac{1}{2}$-inch solar image, ordinarily preferable in Pasadena to a 6.7-inch solar image for photography with the spectroheliograph.

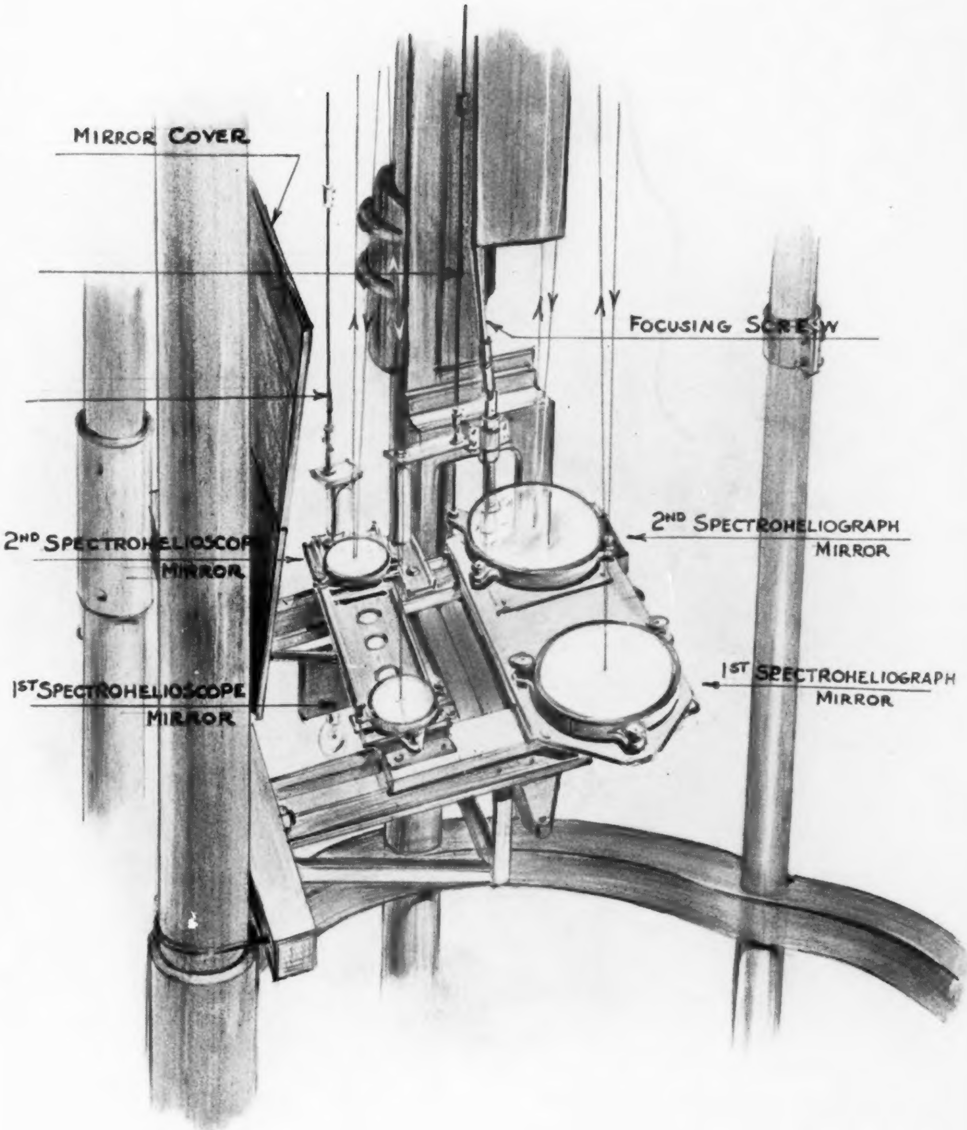
An independent spectrohelioscope, of the horizontal type described in the first part of this article, may also be used as a guide in work with a spectroheliograph. The advantage of my combined ar-

PLATE XXI



Slits, Gratings, and Skeleton Tube of Combined Instruments
Seen from Below

PLATE XXII



CONCAVE MIRRORS OF SPECTROHELIOGRAPH AND SPECTROHELIOSCOPE

rangement appears in cases where it is desirable to bring a small region in the hydrogen atmosphere, otherwise invisible, exactly upon the fixed slit of a spectrograph; or, vice versa, to bring such an object as an invisible sun-spot, betrayed by visual observations of the oscillating Zeeman effect in the 75-foot spectrograph, into the center of the field of view of the spectrohelioscope, in order to learn whether the hydrogen at any level is appreciably affected above the magnetic field.

A word may be added regarding a compound eyepiece, not shown in the illustration, by means of which the (fixed) distorted $H\alpha$ line can be observed in half the field of view, while the other half shows the spectrohelioscope image of the same region. In this way the motion forms can be directly compared with the effects given by rotating the line-shifter.

SOLAR ERUPTIONS AND TERRESTRIAL PHENOMENA

In July, 1892, a brilliant eruption associated with a large sun-spot, followed the next day by an intense terrestrial magnetic storm, was photographed with the Kenwood spectroheliograph.[1] Since that time I have continued to hope that similar methods might permit the detection of all such eruptions and the determination of their exact relationship with auroras, magnetic storms, and other terrestrial phenomena. At present the spectroheliographs in England, France, Spain, Italy, India, and the United States serve this purpose in part, and a number of similar eruptions, also followed by magnetic storms, have been photographed at the Yerkes, Mount Wilson, Meudon, and Kodaikanal observatories.[2] The large unfilled gaps in longitude and the impossibility of taking photographs at sufficiently short intervals nevertheless leave the solar record very incomplete, and further steps must be taken to amplify it.

On January 24, 1926, while testing my first spectrohelioscope between 11^h40^m and 12^h15^m P.S.T., I observed a bright eruption in and following the great spot-group then visible (latitude about 22° N.). Its form changed rapidly, and $H\alpha$ was so much distorted in

[1] Hale, *Astronomy and Astrophysics*, **11**, 611, 1892. Illustrated in my subsequent paper (*ibid.*, p. 917).

[2] Fox and Abetti, *Astrophysical Journal*, **29**, 40, 1909; D'Azambuja and Grenat, *L'Astronomie*, **40**, 489, 1926, and papers by Royds and Nicholson.

places that the rapidly descending dark flocculi could be seen when the second slit was displaced far beyond the line toward the red. On January 25 the eruption, then extraordinarily brilliant, continued throughout the morning and most of the afternoon. The sodium lines D_1 and D_2 and the helium line D_3 were brightly reversed in the large spot. At certain points following the spot, D_3 appeared dark and greatly distorted toward the red. The next morning the great eruption seemed to be over, but at noon a small bright eruption was seen for a few minutes on the edge of the bridge in the large spot. On January 27 another small and short-lived eruption was seen near the large spot. Subsequently I learned from Professor Störmer that he observed at Oslo on the evening of January 26 the brightest (red) aurora he had seen for years. On January 26 the most intense magnetic disturbance in five years was recorded at the Royal Observatory, Greenwich. According to a note in *Nature* for February 6, "the disturbance commenced at $16\frac{1}{2}$ h., rose to a considerable maximum, and subsided soon after 5 h. on the following morning."[1]

This observation, made while the spectrohelioscope was still in the experimental stage, convinced me of the importance of devising such inexpensive instruments as I have described in this paper, and arranging, if possible, for their co-operative use at widely distributed stations. At least seventeen of these instruments will soon be in operation, including two or more in England, one in Italy, one in Syria, one in Australia, one in New Zealand, one in Samoa, three in California, one in South Dakota, one in Michigan, one in Wisconsin, one in Illinois, two in Ohio, and one in New York. Several other spectrohelioscopes will also be installed at intermediate longitudes in the near future, and I therefore hope that within a short time a satisfactory scheme of observations may be in progress.

The spectrohelioscope is especially suited for this work because of the brief time needed to examine the whole disk of the sun and to detect signs of activity calling for vigilance on the part of the observer. Not only astronomers, physicists, and geophysicists, but also students of radio can advantageously join in our co-operative undertaking, because of the relationship that may exist between solar

[1] Hale, *Mt. Wilson Communication*, No. 97; *National Academy of Sciences Proceedings*, **12**, 286, 1926.

outbursts and radio transmission. The task of each observer will be a simple one. He will merely be asked to examine the sun several times a day, if possible at certain hours dependent upon his longitude, and to note the approximate position, area, and brightness of any exceptionally bright flocculi.

Several other applications of the spectroheliocope have been mentioned in previous articles,[1] including its use in connection with the classification of sun-spots, the study of the relationship between prominences and flocculi, and the investigation of the fields of force in the atmosphere of the sun. These will be discussed more fully in the detailed account of my visual observations of the hydrogen flocculi which will form the subject of a later paper.

In connection with the designing of the instruments described in this paper I owe my thanks to Messrs. Pease and Nichols, by whom most of the working drawings were prepared, and to Mr. L. R. Hitchcock, who has made many alterations and improvements and assisted me in the observations. I am also indebted to the members of the staff of the Mount Wilson Observatory who made the spectroheliograms, and to Mr. Russell W. Porter for the perspective drawings reproduced among the illustrations.

CARNEGIE INSTITUTION OF WASHINGTON
MOUNT WILSON OBSERVATORY
October 1929

[1] See Hale, *ibid.*, and *Nature*, **119**, 708, 1927.

THE UNIT CHARACTER OF MULTIPLETS[1]

By CHARLES E. ST. JOHN

ABSTRACT

1. *Unit character of multiplets.*—Nine strong *Fe* multiplets in the violet with a range of line intensity within the multiplet of 2–40 give a red shift of +0.0104 A for strong and +0.0100 A for weak lines; 4 of medium strength with a range of line intensity of 1–6 give +0.0077 A for strong and +0.0074 for weak; 8 in the red with a range of line intensity of 1–9 give +0.0089 for strong and +0.0087 for weak lines. In a total of 154 lines *73 strong lines give +0.0094 A* and *81 weak lines +0.0092 A*. Lines on the main diagonal of the multiplet diagrams are taken as strong, on the side diagonals as weak.

2. The calculation of theoretical intensities, the calibration of the Rowland scale of intensities, the deduction of the number of atoms per square centimeter from line contours, and the equal red shift for the lines in a multiplet, whatever their intensity, imply in the sun *definite layers of maximum absorption.*

3. *Heights from flash spectra.*—Lines of mean intensity 6.5 in multiplets of maximum intensity 20–40 are higher by 400 km than lines of the same intensity in multiplets of maximum intensity 6–7, but owing to photographic errors are measured somewhat lower than the strongest lines in the multiplet.

Introduction.—It has been the practice in discussions of solar phenomena varying with line intensity, such as height, excitation potential, and solar rotation, to consider the intensities of individual lines in looking for correlations. It was thought that the absorbing layers of strong lines only were at great heights above the photosphere. Recent theories of the formation of absorption lines and their application to the quantitative determination of the constituents of the solar atmosphere seem to call for a reconsideration of the older view. The large number of normal *Fe* multiplets identified in the *Rowland Revision*[2] and the new and accurate wave-lengths[3] of the *Fe* lines in the vacuum arc furnish a body of data suitable for the purpose. It has been assembled and discussed in the present paper.

Red shift and line intensity.—The data for the strong *Fe* multiplets with maximum line intensity 10–40 and with low excitation potentials are assembled in section A of Table I. All measured lines are used, and the division between strong and weak lines within the multiplet is made by taking the lines on the main diagonal in the multiplet diagram as strong and those on the side diagonals as weak.

[1] *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 389.

[2] *Publications of the Carnegie Institution of Washington*, No. 396; *Papers of the Mount Wilson Observatory*, **3**, 1928.

[3] Burns and Walters, *Publications of Allegheny Observatory*, **6**, 11, 1929.

The principles of selection are illustrated in the accompanying diagram where the lines on the main (right) diagonal form distinctly the stronger group. The lines on the weaker of the two side diagonals are not considered; λ 3940, because it is a blend with *Co;* λ 3917, because of the strong companion 0.06 A to the red; and λ 3898 for similar reasons. Although the average intensity of the lines on the

MULTIPLET DIAGRAM FOR $A^5F-b^5D^\circ$, SHOWING RED DISPLACEMENTS FOR INDIVIDUAL LINES

($\Delta\lambda = \lambda$ sun *minus* λ vac.; unit = 0.001 A)

	a^5F_5	a^5F_4	a^5F_3	a^5F_2	a^5F_1
$b^5D^\circ_4$	Int. = 25 λ 3820 Δλ = 10	7 3887 11	5 3940 *Fe, Co* 13		
$b^5D^\circ_3$		Int. = 20 λ 3825 Δλ = 10	8 3878 9	5 3917. Line (2) 0.06 A to the red	
$b^5D^\circ_2$			Int. = 10 λ 3834 Δλ = 10	6 3872 9	5 3898 *Fe,V.* Line(2) 0.08 A to the red
$b^5D^\circ_1$				Int. = 8 λ 3840 Δλ = 9	7 3865 10
$b^5D^\circ_0$					Int. = 10 λ 3849 Δλ = 10

main diagonal is 14.6 and on the side diagonal 7, the mean red displacement for the two groups of lines is the same. Nine strong and 4 weak multiplets in the violet and 10 of the strongest in the red have been treated in the same manner. The results are given in sections A, B, and C of Table I. The precision with which this like red displacement holds for lines of widely different intensities in multiplets is indicated by the fact that in a total of 154 lines 73 strong lines give $\Delta\lambda = 0.0094$ and 81 weak lines give $\Delta\lambda = 0.0092$ A, respectively.

Theoretical grounds.—The theoretical calculation of the relative intensity of any line in a multiplet is based upon the quantum numbers for all the lines in the multiplet and upon the correspondence principle. In calculating line intensities by the sum rule it must be applied, according to Ornstein and Burger,[1] to the squared amplitudes of "fictive radiators" which are assumed to represent or to be

[1] *Zeitschrift für Physik*, 40, 412, 1926.

proportional to the number of atoms concerned in the production of the lines. This assumption was used by Russell, Adams, and Moore[1] in the calibration of the Rowland scale of intensities.

In Unsöld's method[2] of deducing the number of atoms from line

TABLE I

RED SHIFT OF SOLAR LINES IN MULTIPLETS

($\Delta\lambda = \lambda$ sun *minus* λ vac.; unit = 0.001 A)

Multiplet	Region	Intensity Range within the Multiplet	On Main Diag.		On Side Diag.		E.P. in Volts
			No. of Lines	$\Delta\lambda$	No. of Lines	$\Delta\lambda$	
A. Violet: Strong Multiplets							
$a^5F - a^5G^\circ$..........	3583–3647	4–20	5	8.4	4	8.8	0.93
$a^5D - a^5F^\circ$..........	3679–3748	6–40	4	9.2	3	9.7	.06
$a^5F - b^5F^\circ$..........	3687–3799	4–40	5	10.8	8	9.0	0.93
$a^3F - b^3D^\circ$..........	3815–3966	3–15	3	9.7	3	12.3	1.54
$a^5F - b^5D^\circ$..........	3820–3940	5–25	5	9.8	4	10.0	0.93
$a^5D - a^5D^\circ$..........	3824–3930	6–20	4	11.2	8	10.4	0.06
$a^3F - b^3F^\circ$..........	3969–4143	7–30	3	11.7	4	11.0	1.54
$a^3F - a^3G^\circ$..........	4147–4325	4–15	3	12.7	3	9.3	1.54
$a^3F - a^5G^\circ$..........	4337–4415	2–15	3	12.3	4	11.0	1.54
Means and totals	....	....	35	10.4	41	10.0	1.01
B. Violet: Multiplets of Medium Strength							
$a^3H - a^3H^\circ$..........	3619–3672	1–5	3	6.3	4	5.8	2.42
$a^3G - a^3H^\circ$..........	3937–4021	3–6	3	7.3	1	9.3	2.68
$a^5P - a^5P^\circ$..........	3943–4038	2–6	2	9.0	2	8.5	2.19
$a^5D^\circ - b^5F$..........	4565–4736	1–6	4	8.2	4	8.0	3.24
Means and totals	....	....	12	7.7	11	7.4	......
C. Red: Strong Multiplets							
$b^3F - b^3F^\circ$..........	6005–6322	1–7	3	10.5	3	6.8	2.57
$a^3H - a^3G^\circ$..........	6136–6344	4–9	2	8.5	3	8.0	2.43
$b^3F - b^3F^\circ$..........	6005–6322	1–7	3	10.5	3	6.8	2.57
$a^5P - b^5D^\circ$..........	6137–6430	3–6	3	6.8	6	8.1	2.19
$a^5P - a^5D^\circ$..........	6232–6411	3–8	3	7.7	4	7.8	3.63
$a^3P - a^3P^\circ$..........	6254–6478	2–7	2	10.5	3	11.0	2.38
$a^5F - a^7F^\circ$..........	6280–6625	1–8	4	7.9	3	10.5	0.93
$a^3H - a^5G^\circ$..........	6318–6593	2–8	3	10.8	2	12.0	2.42
$a^3G - b^3F^\circ$..........	6546–6806	1–6	3	11.2	2	10.5	2.72
Means and totals	....	....	26	9.3	29	8.8	......

[1] *Mt. Wilson Contr.*, No. 358; *Astrophysical Journal* **68**, 1, 1928.

[2] *Zeitschrift für Physik*, **44**, 793, 1927; **46**, 765, 1928.

contours, it is assumed that in a close doublet or triplet the "oscillating power," f, gives the proportion of atoms involved in a given transition and that the equal numbers N obtained for the individual lines represent the total number of atoms over one per square centimeter concerned in producing the lines of the multiplet.

These assumptions have no evident *raison d'être* unless they refer to the same body of absorbing material, and the observed equal red displacement for all lines in a multiplet puts the underlying assumptions upon a definite observational basis.

For the 9 strong multiplets (Table I, section A) the mean red shifts for lines ranging in solar intensity from 2 to 40 are equal. Since all the lines in a multiplet, whatever their intensities, give equal red displacements, it appears that the large red displacements characteristic of strong lines are not due, as sometimes stated, to an "intensity equation," according to which one measures strong and weak lines differently.

Data for multiplets in which the maximum line intensity is 6 are given in section B of Table I. The spectral region is approximately the same as for section A. The mean red displacements for lines in these multiplets, ranging in solar intensity from 1 to 6, are also equal, but definitely smaller than those of section A. Thus the lines of intensity 6 in section A give a mean for the group of 0.0102 A, while lines of the same intensity in section B give a mean of 0.0077 A. We can therefore no longer speak of the red shift of a line of intensity 40, 10, or 6 per se, but only of the lines in a 40-multiplet, a 10-multiplet, or a 6-multiplet where 40, 10, and 6 are the maximum intensities in the separate multiplets.

Heights from flash spectra.—It has been the practice to group the heights of all lines of the same solar intensity and to assume that the mean is the height reached by the corresponding gaseous layers in the sun's atmosphere, for example, for lines of intensity 6. It is evident from sections A and B of Table I that lines of intensity 6 in a 40-multiplet show larger red displacements than lines of intensity 6 in a 6-multiplet, and that the 6's in a 40-multiplet have a much lower excitation potential than the 6's in a 6-multiplet. Do the former also originate in a higher layer? The question is answered by the data in Table II.

The first and second columns of Table II give the multiplet and

TABLE II

HEIGHTS FOR LINES OF LIKE INTENSITY IN MULTIPLETS OF DIFFERENT STRENGTHS

1	2	3	4	5	6	7	8
MULTIPLET	MAX. INT. IN MULTIPLET	LINE	INT.	Δλ	HEIGHT	ON MAIN DIAGONAL	
						Δλ	Height in Km
A. Lines of Intensity 6–7 in Strong Multiplets							
$a^5D-a^5F^{\circ}$....	40	3733.332	7	12.0	....	8.8	1125
		3745.912	6	10.0	....	....	....
$a^5D-a^5D^{\circ}$....	20	3824.454	6	9.0	1000	....	....
		3878.583	7	9.0	1200	11.0	1190
		3895.669	7	11.0	1000	....	....
$a^5F-b^5D^{\circ}$....	25	3865.535	7	9.5	900	....	....
		3872.506	6	8.5	700	10.5	1250
		3887.061	7	8.5	600	....	....
		3940.892	5	11.5	600	....	....
$a^3F-b^3F^{\circ}$....	30	4005.256	7	10.5	800	11.5	950
Means...	....	3839.537	6.5	10.2	850	10.4	1100
B. Lines of Intensity 6–7 in Medium Multiplets							
$a^5F^{\circ}-x^3G$....	7	3716.452	7	8.0	400	7.3	450
$a^5P-a^5D^{\circ}$...	6	3807.546	6	6.0	500	8.5	500
$a^3G-a^3H^{\circ}$...	6	3956.688	6	9.0	....	8.2	....
$a^5P-c^5P^{\circ}$....	6	3974.766	6	6.0	500	2.7	550
		3977.752	6	9.0	....	....	....
$a^5D^{\circ}-b^5F$....	6	4736.783	6	8.0	400	8.2	....
Means...	....	3878.330	6.2	7.7	450	8.0	500
C. Lines of Intensity 3–5 in Strong Multiplets							
$a^3F-b^3D^{\circ}$....	15	3888.526	5	10.0	....	10.3	850
$a^5F-b^5D^{\circ}$....	25	3940.892	5	11.5	600	10.0	1250
$a^5F-b^5F^{\circ}$....	40	3727.636	4	14.5	500	10.0	1000
$a^3F-a^3G^{\circ}$....	15	4147.677	4	6.0	400	11.0	750
$a^3F-b^3D^{\circ}$....	15	3966.075	3	10.0	500	10.3	850
Means...	....	....	4.2	10.4	500	10.3	1175

TABLE II—*Continued*

1	2	3	4	5	6	7	8
Multiplet	Max. Int. in Multiplet	Line	Int.	$\Delta\lambda$	Height	On Main Diagonal	
						$\Delta\lambda$	Height in Km
D. Lines of Intensity 3–5 in Weak Multiplets							
$a^5F^\circ-c^5D$....	5	4084.503	5	10.0	400	8.5	400
$b^3P-d^3D^\circ$...	5	4134.687	5	8.0	500	7.5	480
$b^3F-c^3F^\circ$....	4	3779.433	4	....	500	....	500
b[illegible]P $-b^3P^\circ$....	4	4154.507	4	6.0	500	6.7	500
b[illegible]F $-b^3G^\circ$...	3	4011.416	3	6.0	350	5.3	350
Means...	....	....	4.2	7.5	430	7.0	465

its maximum intensity; the third and fourth, the individual lines and their intensity; the fifth and sixth, the displacement to the red and the heights for the lines considered; and the seventh and eighth, like data for the lines on the main diagonal. Sections A and B supply one set of comparisons and sections C and D a second set. The mean intensity of the lines considered in the first set is 6.4 and in the second 4.2. The spectral regions are approximately the same.

Lines in strong multiplets.—Since the lines in a multiplet originate in the same absorbing layer, the images on flash-spectrum plates are images of the same crescent but made by radiations of widely different intensities. The densities of the images depend upon the strength of the lines and upon the sensibility and threshold value of the photographic plate. The heights of the weak lines estimated from these images will be too low; the deficit for them should increase with increased difference of intensity between the weak and strong lines, and for lines of relative intensity 3–40 it should be larger. The observations show that the lines of mean intensities 6.5 and 4.2 in multiplets of strength 15–40 have heights of 850 and 500 km, respectively, while for lines on the mean diagonal the height is $\approx$ 1100 km. The red displacement is, however, the same for all.

Lines in weak and strong multiplets.—Since the absorbing layers for strong multiplets are higher than for weak multiplets, the heights for lines of the same solar intensity measured on flash-spectrum

plates should on the whole be greater for the strong multiplets. The observations in the third and fourth columns of the summary of Table II show just this, and not only this, but also that the red displacement for high ($\approx$ 1100 km) absorbing layers is larger than for low ($\approx$ 500 km) layers; namely, 0.0103 and 0.0076 A in the mean.

SUMMARY OF DATA IN TABLE II

1	2	3	4		5	
Set	Mean Int. of Compared Lines	Strength of Multiplet	Lines Compared		Lines of Main Diag.	
			$\Delta\lambda$ A	Height in Km	$\Delta\lambda$ A	Height in Km
1	6.5	20–40	0.0102	850	0.0104	1100
	6.2	6–7	.0077	450	.008	500
2	4.2	15–40	.0104	500	.0103	1175
	4.2	3–5	0.0075	430	0.007	465

The results for lines of equal solar intensity show that intensity is not the sole cause controlling height in flash spectra, as lines of the same intensity in strong and weak multiplets give heights of 850 and 450, and 500 and 430 km, respectively, the difference being due to the different elevations of the absorbing layers.

Envoy.—The unit character of multiplets places correlations depending on line intensity upon a new basis and suggests a review of former findings. This has been done for the observations on the outflow from spots[1] and for the data on red displacement and relativity.[2] In both cases the results are more consistent and the conclusions strengthened.

Carnegie Institution of Washington
Mount Wilson Observatory
November 1929

[1] *Mt. Wilson Contr.*, No. 69; *Astrophysical Journal*, **37**, 322, 1913.

[2] *Mt. Wilson Contr.*, No. 348; *Astrophysical Journal*, **67**, 195, 1928.

EXCITATION POTENTIAL IN SOLAR PHENOMENA[1]

By CHARLES E. ST. JOHN

ABSTRACT

1. *Excitation potential fixes the relative heights of the effective absorbing layers* above the photosphere. High values of excitation potential require the stronger fields of excitation obtaining near the photosphere in order to excite the needed number of atoms to the energy-levels of absorption (Table I).

2. *Low heights* above the photosphere of absorbing layers for *multiplets with high excitation potential* are shown by correlating excitation potential with outflow from spots, heights from flash spectra, red displacement, and line intensity, in graphs 1, 2, 3 of Figure 1.

3. The absorbing layers for *intersystem lines* of a given excitation potential are *nearer* the photosphere than those for *normal lines* of the same excitation potential (Table V). The low transition probability for intersystem lines requires the greater abundance of atoms obtaining at the higher pressure near the photosphere.

4. *Excitation potential determines* (1) the possibility and relative probability of the occurrence of a line in the sun's spectrum; (2) the relative heights of absorbing layers above the photosphere; (3) in connection with transition probability, the maximum line intensity in a multiplet; and (4) the temperature classification (Table VI).

5. *Small changes in the energy-level of the higher term* are associated with profound changes in the character of the lines and furnish the basis for a fundamental classification (Table VII).

Introduction.—The importance of excitation potential in showing the relative heights above the photosphere of the absorbing layers in which different Fraunhofer lines originate was noted by the writer in *Mount Wilson Contribution* No. 348.[2] The conclusion (Abstract) was that any one of five methods may be used to allocate the relative levels of origin: (1) solar rotation, (2) Evershed effect, (3) flash spectra, (4) excitation potential, (5) deviations from relativity predictions. In the paragraph on titanium the subject was further discussed. At that time the relation between heights and excitation potential was obtained by forming groups of lines of the same solar intensity and comparing their heights with the corresponding excitation potential. In *Contribution* No. 389[3] it was shown that the multiplet acts as a unit, that the lines in a given multiplet have important characteristics in common, among them equal displacements to the red, whatever the line intensities may be.

[1] *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 390.

[2] *Astrophysical Journal*, **67**, 195, 1928.

[3] *Ibid.*, **70**, 312, 1929.

Accordingly, in the present paper the multiplet is treated as the unit. The basic data are the red displacement, λ sun *minus* λ vac., the velocity of outflow from spots, and the heights in the reversing layer obtained from flash spectra for the normal multiplets of neutral iron. These define the characteristics of the individual multiplets with which the excitation potentials in the *Rowland Revision*[1] are compared. A multiplet will be designated as a 30-multiplet, a 6-multiplet, etc., the numerals giving the maximum line intensity in the multiplet.

Height of absorbing layers.—Eddington in a paper on "The Formation of Absorption Lines"[2] finds that the lines giving the lowest emergent radiation, the blacker lines, refer to absorbing layers at the least optical depth, and that the weaker lines are to be referred to layers at greater depths; for example, for moderately strong lines, $\tau \approx 0.16$, and for weak lines, $\tau \approx 0.58$. Data showing the height of absorbing layers above the photosphere are presented in Table I.

The multiplets and their spectral regions are given in the first column of Table I. The line intensity, number of lines, λ sun *minus* λ vac., Evershed effect, height, and excitation potential are shown in the second, third, fourth, fifth, sixth, and seventh columns, respectively. The data in the fourth, fifth, and sixth columns indicate relative heights above the photosphere.

It has long been recognized that the red displacement of solar absorption lines is greater for lines originating in the upper levels of the sun's atmosphere. The fourth column shows that the red displacement for lines in the first section of the table is 0.0112 A, while for lines of like intensity and wave-length the red displacement as shown in the second section of the table is 0.0092 A. The velocity of horizontal outflow from sun-spots for lines in the reversing layer increases with depth, in this case from 0.42 to 0.84 km/sec., as shown in the fifth column. The sixth column shows the height of the reversing layer for the two groups of lines from measures of their reversals in the flash spectrum. These all march with excitation potential in such a way as to indicate that lines due to transi-

[1] *Publications of the Carnegie Institution of Washington*, No. 396; *Papers of the Mount Wilson Observatory*, **3**, 1928.

[2] *Monthly Notices*, **89**, 627–629, 1929.

tions from high energy-levels originate in low layers of the sun's atmosphere.

Excitation potential depends upon the configuration of the electrons in the atom and not upon the position of the atom. The

TABLE I

CORRELATION OF EXCITATION POTENTIAL, RED SHIFT, OUTFLOW FROM SPOTS, AND HEIGHT

($\Delta\lambda = \lambda$ sun *minus* λ vac.; unit=0.001 A)

Multiplet, Region	Int. of Line	No. of Lines	$\Delta\lambda$	Evershed Effect in Km/Sec.	Height* in Km	E.P.
		A. Pressure Class *a*				
$a^5F-a^5D^\circ$	4	1	14.0	....	500	1.007
5269–5506	5	4	10.8	....	450	0.988
	6	3	8.7	....	570	.975
	7	2	12.5	....	650	.932
	8	2	13.0	....	500	0.933
Means and totals	6	12	11.2	0.42 out	575	0.967
		B. Pressure Class *d*				
$a^5D^\circ-b^5D$	3	3	7.5	....	315	3.242
5208–5393	4	2	9.0	....	375	3.260
	5	2	8.5	....	375	3.246
	6	2	9.0	....	300	3.260
	7	1	12.0	....	....	3.199
$a^5G^\circ-y^5F$	5	2	7.0	....	425	4.324
5367–5424	6	3	11.7	....	350	4.375
$a^5G^\circ-(wy)$	5	1	8.0	....	300	4.294
5364						
$a^5G^\circ-(vy)$	6	1	11.0	....	400	4.302
5393						
Means and totals	5	17	9.2	0.84 out	350	3.752

* Mitchell, *Astrophysical Journal*, **38**, 407, 1913.

magnitudes in the fourth, fifth, and sixth columns change with excitation potential, and are to be regarded as functions of the excitation potential, which is the fundamental physical characteristic.

According to current views, equal line intensities imply equal numbers of atoms in the respective excited states. To attain ap-

proximate equality between the 8-multiplet (Table I, A; E.P. 0.967) and the multiplets 5-7, the lines having mean excitation potential 3.752 volts must originate where the field of excitation is stronger—that is, nearer the photosphere, hence in a deeper-lying portion of the reversing layer. This is shown by the summarized data taken from the fourth to the seventh columns of Table I and given in Table II.

This view is in harmony with findings in the furnace.[1] Lines of class *a* (low E.P.) appear at the lowest temperature, and lines of class *d* (high E.P.) only at the highest temperature, if at all. The enhanced lines of high ionization potential are quenched by adding

TABLE II

SUMMARY

Section	4	5	6	7
	λ Sun *minus* λ Vac. A	Outflow from Spots in Km/Sec.	Height in Km	Excitation Potential
A.	0.0112	Vel. = 0.42	575	0.967
B.	0.0092	Vel. = 0.84	350	3.752

to the furnace an element, such as caesium, of the lowest-known ionization potential. In the sun and in the furnace, the atoms which are activated by the least energy appropriate the major portion of the available supply.

Excitation Potential and Line Intensity.—The inverse relation between excitation potential and height of the absorbing layers above the photosphere for multiplets of various strengths appears with distinctness from the correlation between excitation and line intensity. The mean excitation potentials for multiplets of different strengths, such as a 5-multiplet, a 4-multiplet, etc., are plotted as ordinates and the line intensities as abscissae in graph 1, Figure 1. The highest excitation potential corresponds to the weakest lines. Lines of intensity −1 and −2 appear at heights of 250 km in flash spectra, and lines of intensity −3 rise so slightly above the photosphere that they do not show at all.

[1] King, *Mt. Wilson Contr.*, No. 66; *Astrophysical Journal*, **37**, 234, 1913; *Mt. Wilson Contr.*, No. 233; *Astrophysical Journal*, **55**, 380, 1922.

Excitation potential and outflow from spots.—The relation of excitation to spectral region and to outflow from spots shows again how it acts as an index of the relative levels of the absorbing layers.

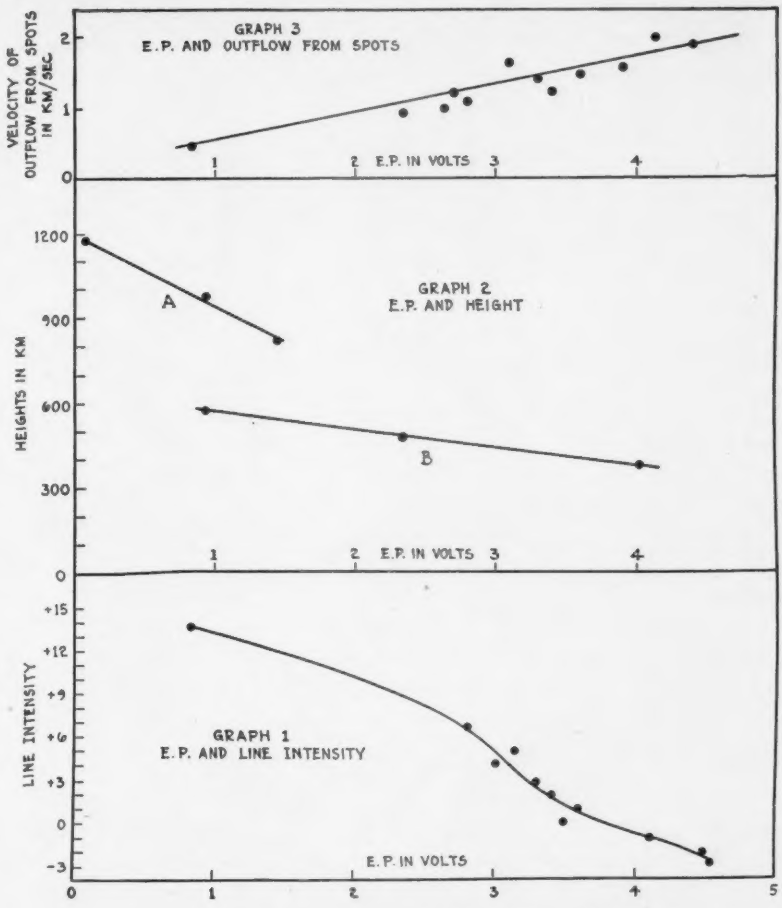


FIG. 1.—Conditions determined by excitation potential

The data are given in Table III. The numbers in the first column are the intensities of the strongest line in the multiplet, and in the second column the mean excitation potential from all multiplets of a given intensity. The third and fourth columns contain in the upper line the mean excitation potential for the two spectral regions, and in the lower line the corresponding velocities of outflow from

spots in km/sec. The fifth and sixth columns give the excitation potentials for the even and odd terms.

An absorption line can be produced only when the atom is already excited to the lower energy state of the transition which produces the line. The excitation potentials of the first column are divided into energy-levels for the even and odd states. For each intensity group the excitation potential of even terms is the lower, which accounts for the predominance of absorption lines in the solar spectrum from even energy-levels. The seventh column gives the east-wind velocity at two levels.

TABLE III

EXCITATION POTENTIAL, SPECTRAL REGION, OUTFLOW FROM SPOTS, EVEN AND ODD TERMS

1	2	3	4	5	6	7
Int. of Multiplet	Mean E.P.	E.P. to Violet of λ 5000 and Outflow	E.P. to Red of λ 5000 and Outflow	Even Terms	Odd Terms	Winds in the Sun
15–40.....	0.83	0.83 0.24	No lines	0.83	None	200 km/hour at height of 1100 km
6–7.......	2.80	2.35 0.9	3.40 1.2	2.47	4.20	100 km/hour at height of 650 km
5.........	3.15	2.65 1.0	3.89 1.5	2.91	3.97	
4.........	3.03	2.77 1.1	3.61 1.5	2.69	4.11	
3.........	3.29	2.68 1.2	3.90 1.6	2.15	4.36	
2.........	3.43	3.28 1.4	4.22 2.0	2.53	4.13	
1.........	3.60	3.11 1.7	4.42 1.9	2.73	4.15	Photosphere

The third and fourth columns show that the excitation potential increases to a striking degree in passing from the violet to the red, and also that this increase keeps step with the velocity of outflow from spots. As this velocity increases with decrease of height above

the photosphere, the higher excitation potential in the red means lower level for the absorbing layers in the red.

In my original paper[1] on outflow from sun-spots it appeared that the velocity of outflow for lines of solar intensity 6, 5, 4, etc., in the red was approximately 0.4 km/sec. greater than for lines of the same intensity in the violet, and the difference was interpreted as evidence that the corresponding absorbing layers corresponding to the red lines were nearer the photosphere. The average change in velocity per Rowland unit of intensity was 0.2 km/sec. The average increase in velocity of outflow on passing from the violet to the red,

TABLE IV

EXCITATION POTENTIAL AN INDEX OF HEIGHT

Max. Int. 15–40		Max. Int. 6–7		Max. Int. 5		Max. Int. 4		Max. Int. 3		Max. Int. 2	
E.P.	Ht. in Km	E.P.	Ht. in Km	E.P.	Ht. in Km	E.P.	Ht. in Km	E.P.	Ht. in Km	E.P.	Ht. in Km
0.06..	1170	2.04	550	2.46	575	2.27	465	2.47	390	2.44	388
0.96..	980	3.80	400	3.80	380	4.18	390	4.13	365	4.21	338
1.24..	875	......	......	......	......	......	......	......	......	......	......

column 4 *minus* column 3, is 0.4 km/sec., which means, as before, that a line of intensity 6 in the red is at the level of a line of intensity 4 in the violet. The effect is too large to be attributed to changes in the Rowland scale of intensities.[2]

The positive correlation coefficient between excitation potential and velocity of outflow from spots is shown by graph 3 in Figure 1, where the abscissae are volts and the ordinates are velocities of outflow. High excitation potential means, then, low heights for the absorbing layers and should show a negative correlation coefficient with heights above the photosphere.

Excitation potential an index of height.—The data in Table IV were obtained by dividing the excitation potentials for each multiplet group into low and high groups and taking the corresponding heights from flash spectra.

[1] *Mt. Wilson Contr.*, No. 69; *Astrophysical Journal*, **37**, 322, 1913.

[2] Russell, Adams, and Moore, *Mt. Wilson Contr.*, No. 358; *Astrophysical Journal*, **68**, 1, 1928.

Graph 2 in Figure 1, besides showing a negative correlation between excitation potential and heights, brings to light somewhat surprising differences in distribution of *Fe* absorbing layers. The discontinuity between sections A and B is real and was foreshadowed by the gap at the high-intensity end of the graph in Figure 1. Three energy-levels only are represented by *Fe* lines at great heights above the photosphere: a^5D, a^5F, and a^3F with the excitation potentials 0.06, 0.96, and 1.54 volts. All the multiplets[1] represented in this high layer originate in these three energy-levels, the total number of lines being 88. All others of the 3157 lines identified with normal iron in the *Rowland Revision* are found below this level. The discontinuity between sections A and B, graph 2, Figure 1, implies a region in the sun's atmosphere, about 300 km in extent, in which no lines due to neutral iron originate. With the present data it is probably pushing the interpretation too far to take seriously the result that a difference of 1 volt in excitation potential means a difference in level of 40 km.

The heights for multiplets of a given excitation potential may be approximately obtained from section B, graph 2. For example, there are six strong multiplets with excitation potentials of 2.19–3.60 volts and of strengths 7–10. If these are arranged in groups of three with mean excitation potentials 2.35 and 3.0, the heights according to the graph are 490 and 450 km; as observed, they are 453 and 425 km.

Intersystem combinations.—Up to this point only normal multiplets of neutral iron have been considered. The conclusion is that high excitation potential indicates low level of the absorbing layer. Intersystem combinations may be compared with normal combinations by the data in Table V. The first column gives the excitation potential; the third, the line intensity; the fifth, sixth, and seventh, the velocity of outflow from spots, the height from flash spectra, and the pressure in the sun's atmosphere. Sections A and B give the data for intersystem and normal combinations having the same energy-level. The fourth, fifth, and sixth columns give criteria for level. These show that the absorbing layer for the intersystem lines is far

[1] Included in the spectral region to the red of λ 3585 remeasured for the *Rowland Revision.*

below that for normal lines. Intersystem combinations mimic normal combinations having higher excitation potentials. For example,

TABLE V

INTERSYSTEM AND NORMAL COMBINATIONS

(λ sun *minus* λ vac. $=\Delta\lambda$; unit $=0.001$ A)

1	2	3	4	5	6	7
Multiplet E.P.	Lines	Intensity	$\Delta\lambda$	Outflow from Spots in Km/Sec.	Height in Km	Pressure Atm.
A. Intersystem Combinations						
$a^5D-a^7P^\circ$:						
0.051	4206.704	3	60.0	....	400	....
.000	4216.193	3	8.0	....	400	....
.110	4232.736	2	9.0	....	400	....
.087	4258.324	2	9.0	1.56	400	....
0.051	4291.475	2	9.0	1.08	500	....
$a^5D-a^7F^\circ$:						
0.000	4347.244	1	9.0	0.96	....	....
.000	4375.946	6	14.0	....	500	....
.051	4389.256	2	8.0	....	500	....
.051	4427.319	5	7.0	....	600	....
.087	4435.158	2	8.0	....	....	....
.087	4461.662	4	7.0	....	500	....
0.121	4483.750	4	10.0	....	400	....
0.058	4343.814	3.0	8.7	1.20	460	$\approx 10^{-3}$
B. Normal Combinations						
$a^5D-a^5D^\circ$:						
0.000	3824.444	6	9.0	....	1000	....
.051	3856.383	8	10.0	....	1600	....
.000	3859.924	20	10.5	....	1600	....
.087	3878.583	7	8.5	....	1200	....
.051	3886.296	15	12.0	....	1600	....
.110	3895.669	7	17.0	0.3	1200	....
.087	3889.721	8	17.0	....	1000	....
.110	3906.492	10	12.0	0.24	750	....
.121	3920.271	10	13.0	....	1000	....
.051	3922.925	12	11.5	....	1200	....
.110	3927.935	8	14.0	....	1000	....
0.087	3930.310	8	11.0	....	1000	....
0.072	3889.182	9.3	11.9	0.27	1175	$\approx 10^{-6}$

the intersystem lines with excitation potential 0.058 given in the second column of Table V behave like normal lines with excitation

3 volts (graphs 1–3, Fig. 1). The transition probability in intersystem combinations is low, as shown by the relative intensity 1–3 for the lines in the second column of sections A and B. The transition probability being low, the production of lines of intensity 5–6 requires that large numbers of atoms be at disposal. These are supplied by the relatively high pressure at the lower level indicated in the seventh column.

Effects depending upon energy-level.—Changes in energy-level are concerned in a number of observations that at first sight do not

TABLE VI

FACTORS FIXED BY ENERGY-LEVEL

LINES	E.P.	MULTIPLET	LEVEL OF HIGH TERM	PRESSURE CLASS: $E<$ Energy-Level $<E_2$ of Higher Term
3906.492	0.110	$a^5D_1 - a^5D^\circ_1$	3.269	2.432 < Class a < 4.012
3906.270	1.478	$a^3F - b^3F^\circ_3$	4.588	4.012 < Class b < 5.123
3997.403	2.176	$a^3G_4 - a^3H^\circ_5$	5.802	5.123 < Class d < 6.790
5415.199	4.354	$a^5G^\circ_4 - 54W_3$	6.632	6.605 < Class e < 6.790

seem to be intimately related to them, but of which they are the *vera causa*. Energy-level serves as a kind of "barometer"; when it changes, other effects follow which may be regarded as functions of it. The second, fourth, and fifth columns of Table VI give essential data, namely, excitation potential, energy-level of the high term, and pressure class.

A. Excitation potential determines:

1. The probability of the occurrence of a line in the sun's spectrum. The lower the excitation potential the higher the probability. For *Fe* lines the range in excitation potential is from 0.000 to 5.064.

2. The position of the absorbing layer:

E.P.	Height in Km
0.06	1100–1200
1.54	850– 950
2.716	450– 500
5.064	250

3. In combination with transition probability, the maximum intensity in the multiplet:

E.P.	Maximum Intensity
0.06	40
1.54	30
2.716	8
5.0[illegible]4	2

4. The temperature class, which changes by 1 unit for a change of 0.72 volt in excitation potential.[1]

B. The energy-level of the higher terms in the combination determines the pressure class, a function of the electronic configuration in the atom in the higher energy state. The four pressure classes are as sharply differentiated as the energy states and include all *Fe* lines identified in multiplets. Classes *a*, *b*, and *d* were proposed by Gale and Adams[2] from the pressure coefficients; class *e*, by St. John and Miss Ware[3] from its negative pole effect. Their connection with the energy-level of the higher term was recently established by Babcock.[4] Data showing the significance of changes in the high-level term are given in the third, fifth, and sixth columns in Table VII.

Small changes in excitation potential have comparatively little effect, but small changes in the energy-level of the higher terms may completely alter the character of the spectral lines. Lines λ 5065 and λ 5090 are produced by transitions from the same lower term $b^5F^\circ_3$ to levels of 6.675 and 6.662 volts, respectively. By this change of 0.013 volt the character of the line is reversed. Line λ 5065 is asymmetrical to the violet and shorter at the pole of the arc than in the center; line λ 5090 is asymmetrical to the red and longer at the pole of the arc. One temperature class represents a fifty-fold greater change in excitation potential. The pressure classification apparently depends upon profound changes in the atom, and by this criterion it is fundamental.

Conclusion.—Five indices of relative levels of the absorbing layers in the sun's atmosphere have been considered. All agree in

[1] *Mt. Wilson Contr.*, No. 350; *Astrophysical Journal*, **67**, 259, 1928.

[2] *Mt. Wilson Contr.*, No. 58; *Astrophysical Journal*, **35**, 10, 1912.

[3] *Mt. Wilson Contr.*, No. 61; *Astrophysical Journal*, **36**, 14, 1912.

[4] *Mt. Wilson Contr.*, No. 350; *Astrophysical Journal*, **36**, 14, 1912.

the order of levels. In historical sequence they are heights from flash spectra, solar rotation, outflow from spots, red displacement of Fraunhofer lines, and excitation potential. In order of precision, because of its exact determination, excitation potential comes first; then, depending upon precision of observation and weight of accumulated data, follow in order red displacement of Fraunhofer lines, outflow from spots, solar rotation, and heights from eclipse spectra, the last being affected by photographic errors.

TABLE VII

EFFECTS PRODUCED BY CHANGES IN THE ENERGY-LEVEL OF THE HIGHER TERM

Line	Int.	E.P.	Multiplet	High Term	Pressure Class*	T Class*
5065.030...	3	4.238	$b^5F^\circ_3-c^3G_4$	6.675	*e* Asymmetrical to violet	V
					Pole-effect negative	
					Pressure coeff. moderate	
					Very high temp. lines	
5090.782...	5	4.238	$b^5F^\circ_3-61W_3$	6.662	*d* Asymmetrical to red	IV
3305.974...	4	2.188	$a^5P_2-c^5P^\circ_3$	5.251	*d* Pole-effect positive	
					Pressure coeff. large	
					High temp. lines	III
4292.296...	2	2.188	$a^5P_2-c^5F^\circ_2$	5.064	*b* Generally symmetrical	
3849.979...	10	1.007	$a^5F_1-b^5D^\circ_2$	4.213	*b* Pressure coeff. medium	II
					Medium temp. lines	
5434.536...	5	1.007	$a^5F_1-a^5D^\circ_0$	3.278	*a* Always symmetrical	I
					Pressure coeff. small	
					Low temp. lines	

* Defined in the *Rowland Revision*, pp. x–xi of Introduction

The energy-levels of the low and high terms in multiplets play distinct rôles. The low term, for example, determines the temperature class; the high term founds the pressure classification upon profound changes in the electron configuration within the atom. Intersystem combinations mimic the behavior of normal combinations with higher excitation potential.

CARNEGIE INSTITUTION OF WASHINGTON
MOUNT WILSON OBSERVATORY
November 1929

INDEX TO VOLUME LXX

SUBJECTS

INDEX TO VOLUME LXX

AUTHORS

Publications of

The YERKES OBSERVATORY

Vol. I. General Catalogue of Double Stars. With illustrations. By SHERBURNE WESLEY BURNHAM. 296 pages, cloth, postpaid $4.15; *net* $4.00

Vol. II. The Decennial Papers on Astronomy and Astrophysics. 414 pages and 29 plates, cloth, postpaid $6.20; *net* 6.00

Vol. III. (Part I.) The Rumford Spectroheliograph of the Yerkes Observatory. By GEORGE E. HALE and FERDINAND ELLERMAN. 26 pages and 15 plates, paper, postpaid 85 cents; *net* 75

(Part II.) The Spectrum of the High Potential Discharge between Metallic Electrodes in Liquids and in Gases at High Pressures. By GEORGE E. HALE and NORTON A. KENT. 42 pages and 8 plates, paper, postpaid 85 cents; *net* 75

(Part III.) The Rotation Period of the Sun. By PHILIP FOX. 136 pages, postpaid $2.60; *net* 2.50

(Part IV.) The Forms and Motions of Solar Prominences. By EDISON PETTIT. 34 pages and 11 plates, paper, postpaid $1.35; *net* 1.25

Vol. IV. (Part I.) Stellar Parallaxes Derived from Photographs Made with the 40-inch Refractor. By FREDERICK SLOCUM, ALFRED MITCHELL, OLIVER J. LEE, ALFRED H. JOY, and GEORGE VAN BIESBROECK. 68 pages and 2 plates, paper, postpaid $1.60; *net* . 1.50

(Part II.) Photographic Investigations of Faint Nebulae. By EDWIN P. HUBBLE. 89 pages, paper, postpaid 85 cents; *net* . . .75

(Part III.) Parallaxes of Fifty Stars. By GEORGE VAN BIESBROECK and HANNAH STEELE PETTIT. 36 pages, paper, postpaid $1.54; *net* 1.50

(Part IV.) Zone $+45°$ of Kapteyn's Selected Areas: Parallaxes and Proper Motions of 1041 Stars. By OLIVER JUSTIN LEE. 67 pages, paper, postpaid $1.55; *net* 1.50

(Part V.) A Comparison of the Photometric Fields of the 6-inch Doublet, 24-inch Reflector, and 40-inch Refractor of the Yerkes Observatory, with Some Investigation of the Astrometric Field of the Reflector. By ALICE HALL FARNSWORTH. 37 pages, paper, postpaid $1.55; *net* 1.50

(Part VI.) Photometric Observations of 1550 Stars in the Kapteyn Areas. By JOHN ADELBERT PARKHURST. 62 pages, paper, postpaid $1.60; *net* 1.50

(Part VII.) Astrometric and Photometric Statistics of Certain of Hagen's Fields Photographed with the 24-inch Reflector. By HARRIET MCWILLIAMS PARSONS. 44 pages, paper; *about* . . 1.50

Vol. V. (Part I.) Measurements of Double Stars. By GEORGE VAN BIESBROECK. 265 pages, paper, postpaid $3.15; *net* 3.00

(Part II.) Definitive Orbit of Comet Delavan. By GEORGE VAN BIESBROECK. 36 pages, paper, postpaid $1.60; *net* 1.50

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO . . . . ILLINOIS

THE NATURE OF THE WORLD AND OF MAN

By Sixteen Members of the Faculty of the University of Chicago

In its new edition this book will continue to serve as a most important factor of the success of the survey course that directs the college Freshman toward the proper orientation to the world and man as science sees them. A completely revised chapter and minor revisions throughout the book appear in this new edition. These changes have been made as a result of additional classroom use, of helpful suggestions from those using the text, and of advances in various fields. Frequent revisions to keep this book abreast of the best educational practice is an important factor in the plan upon which it is based.

The Critics Say—

"One of the finest and most engrossing popularizations of current science in existence. . . . . It is simple, clear, concrete, reliable. One emerges from it the richer by solid information and definite concepts."—Henry Hazlitt, *New York Sun.*

"A manual of the physical and biological sciences of which it would be hard to speak too highly. The volume is so many things that an outline ought to be but frequently is not. It is selective in the sense of plucking the real heart out of a body of data."—*The New York Times Book Review.*

Forest Ray Moulton
"Astronomy"

"For the story is well told, well illustrated, and well colored with human significance. Certainly the volume is accurate; the names of the various contributors guarantee that. Certainly it is interesting and readable, and popular without being diluted."—*The Nation.*

Harvey Brace Lemon
"Energy: Radiation and Atomic Structure"

$4.00, postpaid $4.15

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO . . . ILLINOIS